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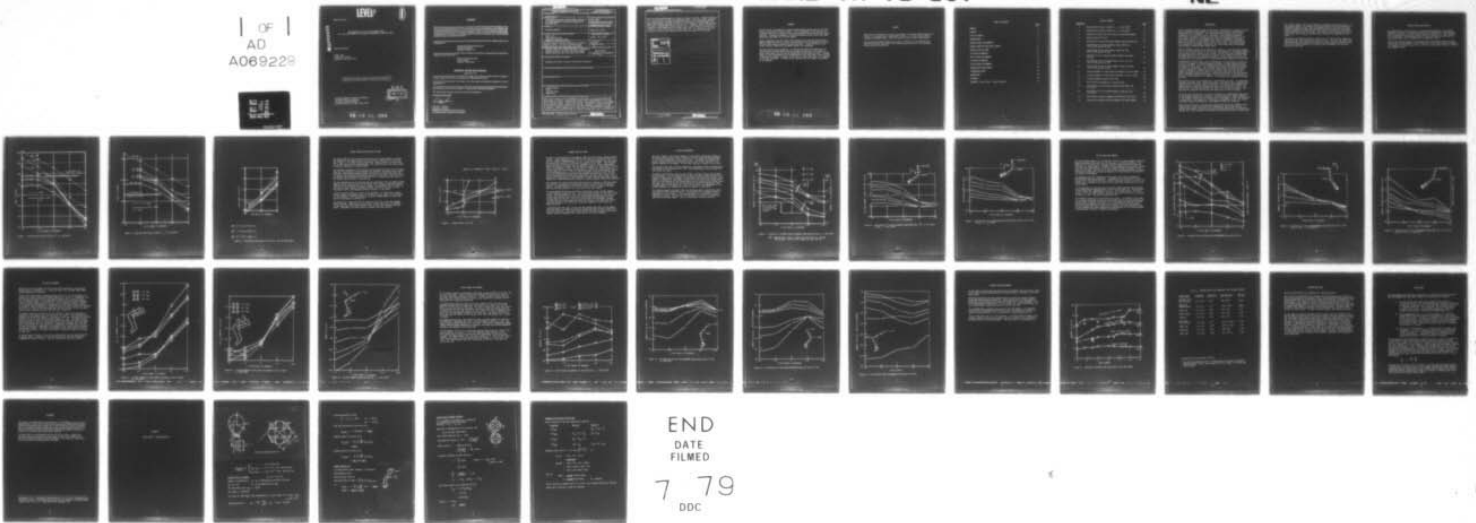
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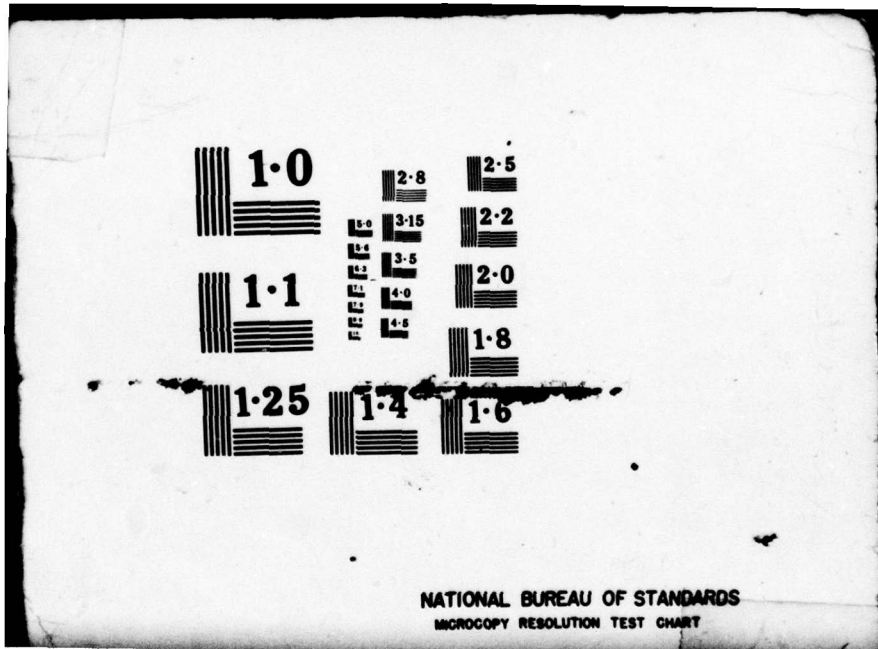
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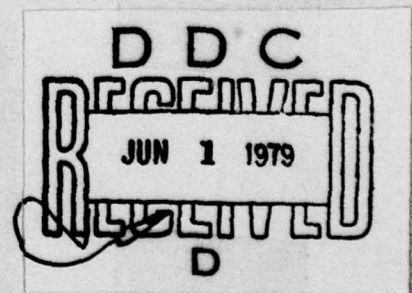
PRELIMINARY ANALYSIS OF WIND TUNNEL TEST
OF A 1/2 SCALE MODEL OF AN EJECTING CREWMAN AND EJECTION SEAT

Alastair Anthony

PAYNE, INC.
1933 Lincoln Drive
Annapolis, Maryland 21401

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Aerospace Medical Research Laboratory
Aerospace Medical Division
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TECHNICAL REVIEW AND APPROVAL

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The experiments reported herein were conducted according to the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council.

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 80-33.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER



WILLIAM J. GANNON
Associate Director
Biodynamics and Bioengineering Division
Aerospace Medical Research Laboratory

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with attitude and Mach number, presents no great surprises. Values critical to the stress analysis confirm the estimated values. The neck pillar, designed by a subcontractor, had been designed for sensitivity in bending under the head loads without catering for torsion in the member if these loads should in the event be appreciably offset from its axis. Although there is little confirmation of the magnitude of the head loads, there is some indication the offsets in excess of one inch in these loads are to be expected in the real situation, and that the resulting torsion was the cause of the failure.

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SUMMARY

Failure of the neck member of a model crewman during tunnel tests of the limb forces during ejection raised doubts as to the integrity of the rest of the structure and on the accuracy of the load estimates used in the pretest stress analysis. Testing was resumed at restricted pressure values with a non-load-measuring replacement for the neck member.

From a sampling of the test data, the distribution of bending and torsional moments along the limbs is clearly revealed and, with its variation with attitude and Mach number, presents no great surprises. Values critical to the stress analysis confirm the estimated values very reasonably.

The neck pillar was an exception. It had been designed for sensitivity in bending under the head loads without catering for torsion in the member if these loads should in the event be appreciably offset from its axis. Although there is little confirmation of the magnitude of the head loads, there is some indication the offsets in excess of one inch in these loads are to be expected in the real situation. A formal stress analysis for this member is included as an appendix.

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PREFACE

This report was prepared in partial fulfillment of Contract Number F33615-76-C-0530. The research was accomplished by Payne, Inc., 1933 Lincoln Drive, Annapolis, Maryland 21401. Peter R. Payne was the Principal Investigator.

The Air Force Technical Monitor was James W. Brinkley of the Biomechanical Protection Branch, Biodynamics and Bioengineering Division of the Aerospace Medical Research Laboratory.

TABLE OF CONTENTS

	<u>Page</u>
SUMMARY	1
PREFACE	2
LIST OF FIGURES	4
INTRODUCTION	5
OVERALL FORCES AND MOMENTS	7
HELMET FORCES AND THE NECK FAILURE	11
GENERAL NOTE ON LIMBS	13
IN-PLANE ARM MOMENTS	14
OUT-OF-PLANE ARM MOMENTS	18
IN-PLANE LEG MOMENTS	22
OUT-OF-PLANE LEG MOMENTS	26
CHANGES WITH MACH NUMBER	31
ALTERNATING LOADS	34
CONCLUSIONS	35
EPILOGUE	36
APPENDIX: Neck Pillar - Stress Analysis	37

LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
1	Drag and axial force at Mach 0.5. $q = 100 \text{ lb/ft}^2$	8
2	Drag and axial force at Mach 1.4. $q = 150 \text{ lb/ft}^2$	9
3	Variation in side force with pitch, yaw and Mach number.	10
4	Helmet forces at 0° yaw.	12
5	Variation in in-plane shoulder moments with pitch and yaw.	15
6	Distribution of in-plane moments along right arm, -30° to $+30^\circ$ pitch, 0° yaw.	16
7	Distribution of in-plane moments along left arm, -30° to $+30^\circ$ pitch, 0° yaw.	17
8	Variation in out-of-plane shoulder moments with pitch and yaw.	19
9	Distribution of out-of-plane moments along left arm, -30° to $+30^\circ$ pitch, 0° yaw.	20
10	Distribution of out-of-plane moments along right arm, -30° to $+30^\circ$ pitch, 0° yaw.	21
11	In-plane moments at right upper leg gauges in yaw to right.	23
12	In-plane moments at left upper leg gauges in yaw to right.	24
13	In-plane moments along the left leg.	25
14	Out-of-plane leg moments vs. pitch and yaw.	27
15	Distribution of out-of-plane moments along right leg at 0° yaw.	28
16	Distribution of out-of-plane moments along left leg at 0° yaw.	29
17	Out-of-plane right leg moments distribution at 30° yaw.	30
18	Increase in shoulder and elbow moments with Mach number.	32

INTRODUCTION

In the continuing quest for data on the forces encountered by a crewman ejected from an aircraft at high speeds, a half-scale model had been designed and fabricated by the contractor. This represented the crewman in the escape configuration in the ACES II seat. The torso, itself non-representative structurally, provided a correct outward form with attachment points for the legs, arms, and neck. These members were built as assemblies of aluminum alloy bones rigidly bolted together at the joints and covered with hardwood flesh to present the correct outer surface of the limbs. The complete model was supported on the balance assembly in the Arnold Engineering Development Center (AEDC) Propulsion Wind Tunnel (16T).

The test schedule called for air speeds up to Mach 1.4, with attitudes ranging +30° to -30° in pitch and 0° to 30° in yaw. Measurements of the bending moments on the limbs were to be made at two stations on each lower leg, thigh, forearm, and upper arm in the two directions, in and out of the plane of the bent limb. The head loads were to be measured by gauges to detect bending of the neck in two directions and extension of it for the upwards force expected on the helmet.

On completion of the design, prior to manufacture and long before installation of the strain gauges at the measurement locations, a formal analysis of the structure was made. This was in compliance with AEDC's published requirements for safety in the tunnels. The estimated loads used in the analysis were for the most part derived from previous tunnel work at full scale and low speed, using live subjects, suitably ratioed to the model half scale and to the mandatory maximum tunnel pressure ($q = 600$ psf) called for in the AEDC requirement. Allowable stresses were taken at one third of yield, or one quarter of ultimate for the materials, as required. This analysis was completed in December 1976.

During fabrication and instrumentation, some changes were made. In particular, the bones were made round, rather than square, in section, which increased the nominal stresses a little, but not critically. The neck pillar, however, was redesigned as a sensitive transducer for the forces acting on the head. The design values for these forces were the same as in the previous analysis and were used to establish the stresses and sensitivity in the new design,

The neck pillar failed early in the test sequence at a comparatively low value of the dynamic pressure ($q = 190$ psf). It was replaced by a member similar to the original design and not equipped with strain gauges. Test then continued to completion of the schedule at 'q' values not exceeding 315 psf. No further structural failure occurred and a large amount of data was collected.

After the neck failure, there was some concern that the actual loading in the tunnel might be more severe than that estimated for the stress analysis. A further test program using the model in the escape sequence was in preparation and for this it was necessary to reaffirm the structural integrity of the model.

For a quick response, it was not possible to examine all the data closely. In the present report, a few samples are transcribed and plotted as moment distributions along the limbs. The corresponding loads at the joints or other critical locations are compared with those used in the analysis, with appropriate adjustment of the 'q' values. To account for the neck failure at such a low value, a new analysis has been made, attached as an appendix to this report.

The data has not been processed in any way, but is taken from the tabulation supplied by the tunnel and plotted "warts and all." At least one gauge fault can be detected, but otherwise, the quality is good enough to show the distribution very clearly and may be of value to those concerned with the main objective of the test.

OVERALL FORCES AND MOMENTS

The overall forces, lift and drag, and the derived components (X,Y,Z,L,M,N) referred to body axes, increase considerably with Mach number. The following plots of drag, axial, and side force for Mach 0.5 and Mach 1.4 show a rise of 30 to 40 percent. The estimated values of axial and side force are good for the subsonic data but are exceeded by the supersonic values.

These larger forces present no strength problems, being well within the capabilities of the AEDC support system. They have little effect upon the stresses in the model, but they do give a hint of what to expect when we come to consider its component parts.

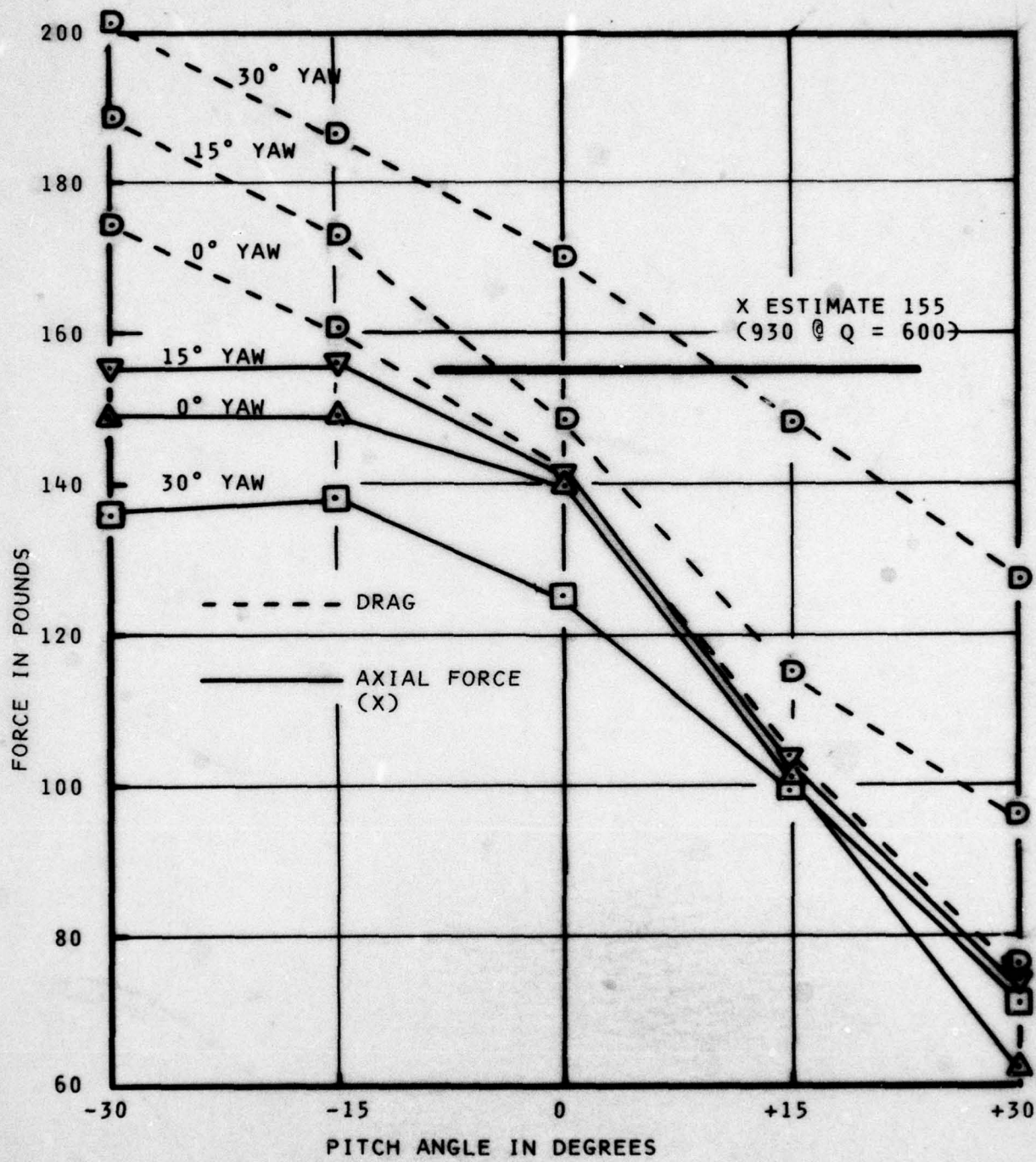


Figure 1. Drag and axial force at Mach 0.5. $q = 100 \text{ lb/ft}^2$

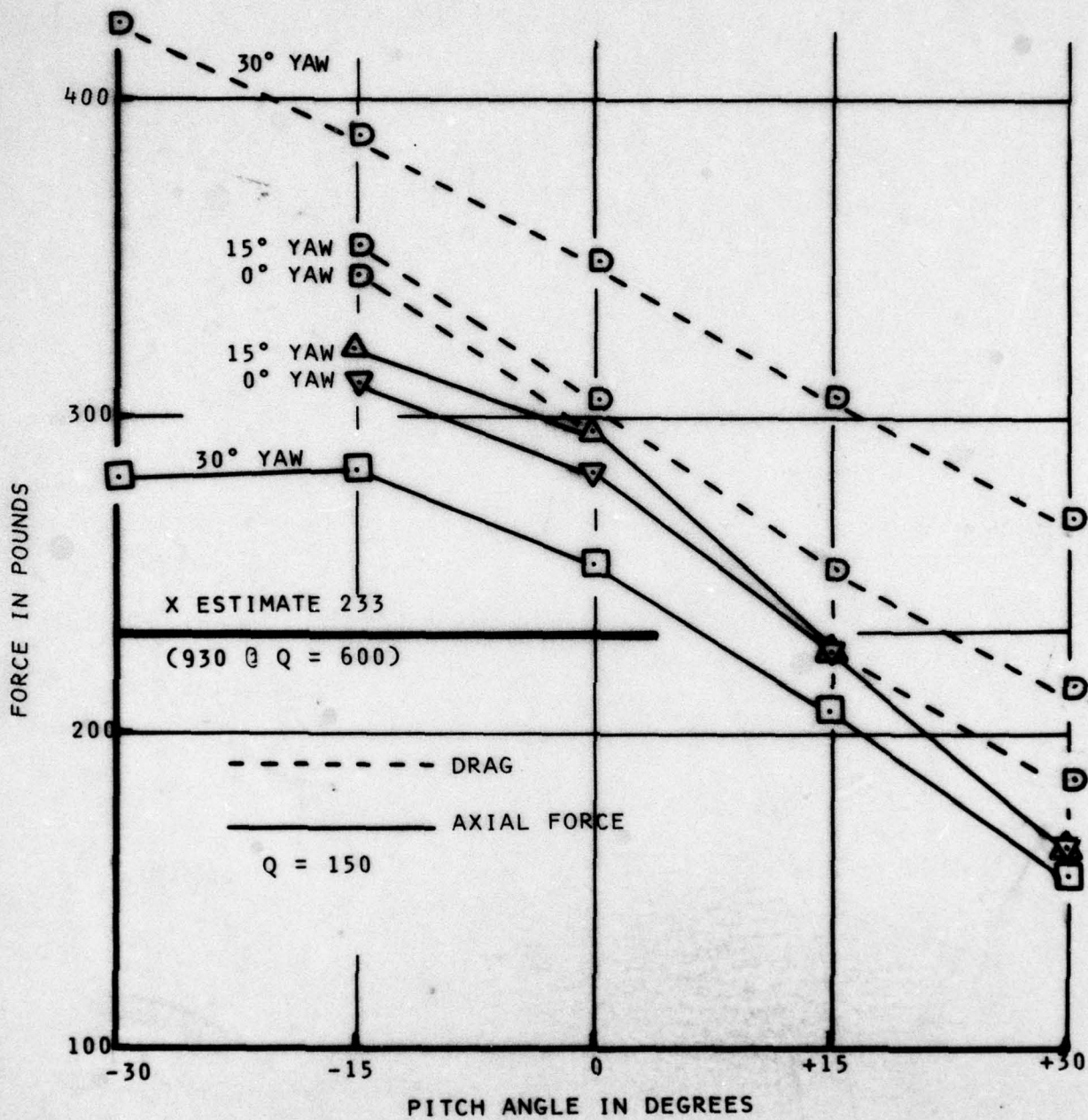
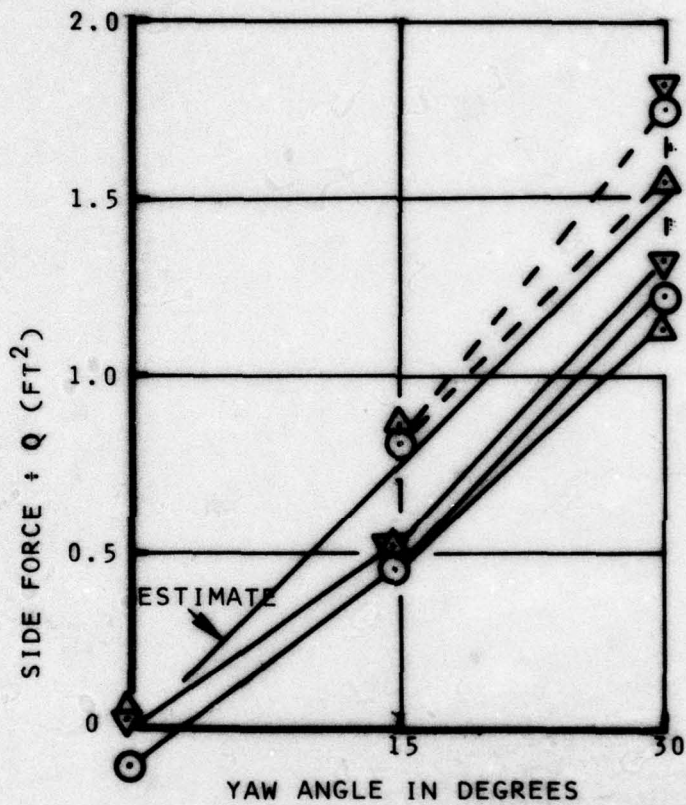


Figure 2. Drag and axial force at Mach 1.4. $q = 150 \text{ lb/ft}^2$



▲ +30° PITCH, MACH 0.5

○ 0° PITCH, MACH 1.4

▼ -30° PITCH, MACH 1.4

Figure 3. Variation in side force with pitch, yaw, and Mach number.

HELMET FORCES AND THE NECK FAILURE

The small amount of data collected before the neck failed appears to confirm our estimate of the upwards force (Z), but shows a rearwards (X) force somewhat larger at -30° pitch than was predicted. There is also a net side force (Y) at zero yaw, which is unpredictable. The differences are not large enough to have any bearing on the neck failure.

The supplier's analysis of the stresses in this member is open to the criticism that the distribution of strain amongst the redundant load paths was not fully explored. The declared maximum stress, 43,000 psi, is little more than half the actual figure obtained by matching the strains correctly. Even so, it does not explain why the piece should have failed at a loading about one third of the design load from which it was derived.

The real mistake was in not allowing for the possibility that the applied loads might be offset from the axis of the member, thus putting a torsional loading additive to the flexural and direct stresses. This omission did not matter in the original solid design, inherently strong and stiff in torsion. In the delicately carved, four-legged transducer version, it was fatal.

A fairly precise analysis is given in the appendix. It shows that, without offset loading, the maximum stress is 83,000 psi, about equal to the ultimate for the material. With the resultant of the X,Y loads offset 0.5 inch, the stress is increased to 146,000 psi.

The actual test loads were (19,2,4) moving to (16,5,11) at the last reading before failure. Compared with the analysis values (45,45,60), the maximum stress would have been around 43,000. This is still not enough to fail the piece. Presumably, the load offset was greater than half an inch.

RUNS 25.2 THROUGH 6, MACH 0.602, Q = 190.4

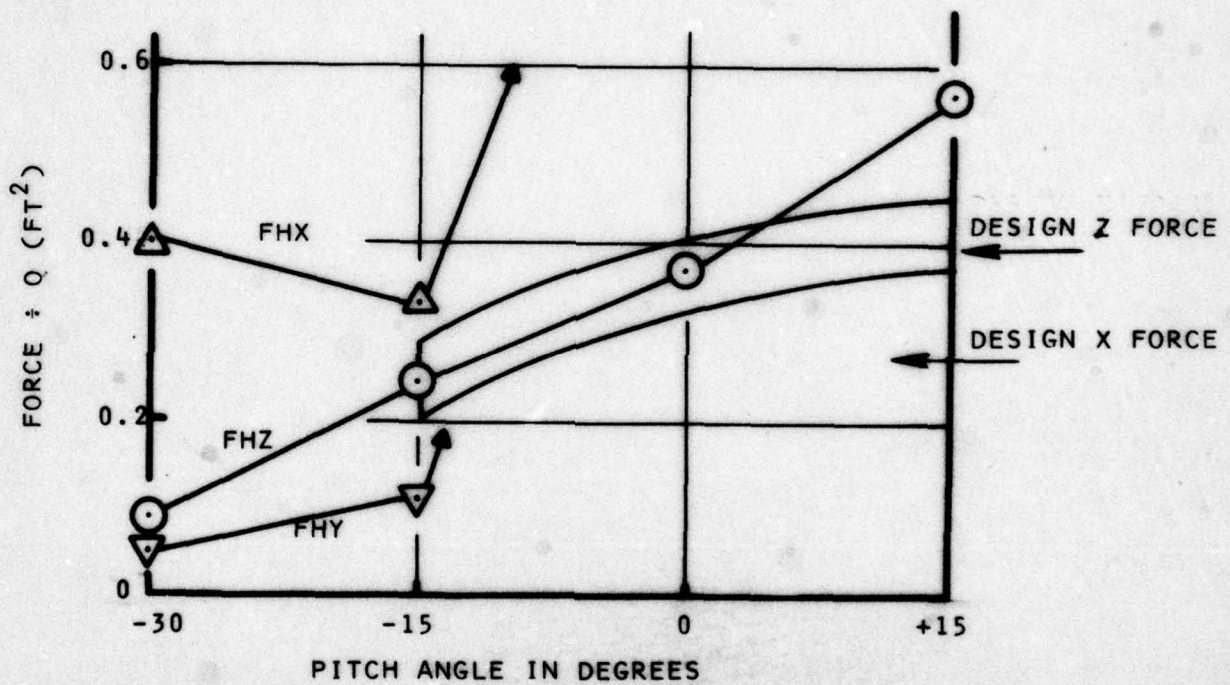


Figure 4. Helmet forces at 0° yaw.

GENERAL NOTE ON LIMBS

An arm or a leg consists of two members, upper and lower, which together define a plane. Loads imposed upon the limb may be either in this plane or out of it, that is, normal or perpendicular, to it. In the model crewman, the limb planes are practically parallel to the plane of symmetry of the model. The in-plane forces can thus be resolved into two components X and Z, and a single moment about the normal axis, while the out-of-plane loading is a single force Y giving rise to two moments L and N. (In the case of a human, the limb plane may be rotated about any axis through the shoulder or hip joint, necessitating rotation of the reference axes.) It is a little misleading to speak of lift and drag, since the downstream direction does not coincide with the body axis, nor are the two transverse lift directions aligned with the body X and Z axes. This is particularly unfortunate in the definition of upper leg lift force FH_{ZL,R} which appears as a large and mysterious quantity located somewhere behind the posterior.

The strength of a limb cantilevered from the hip or shoulder is entirely dependent upon its resistance to the moments (L,M,N) resulting from the applied forces. The shear forces (X,Y,Z) do not matter at all, so long as the shear path has not been destroyed as in the case of the neck support.

The instrumentation provides for direct observation of the in-plane moments at four stations along each limb. The out-of-plane moments are not fully ascertained. The measurement is of an out-of-plane moment normal to the limb axis at the same stations, which gives the out-of-plane bending moment but says nothing about the torsion. We have to assume that the aerodynamic loading is along the axis of the member and that the torsion in the upper part arises from the bending of the lower part, being the component of this about the upper part axis.

In assessing the test data, we rely for the present upon plots of the moments along the limbs, including the figures extrapolated from the data stations to the joint positions. This gives a good picture of what is going on and yields moments directly comparable with those used in the stress analysis.

IN-PLANE ARM MOMENTS

The plot, Figure 5, of in-plane moment at the shoulder versus pitch angle at the various yaw attitudes shows a negative, that is, hand towards knee moment at -30° pitch decreasing to near zero at $+30^\circ$. The moment is evidently due mainly to drag acting on the projected frontal area of the limb and is not greatly affected by yaw angle. In the tests, the yaw is always to the right.

The variation with yaw is fairly progressive, decreasing on the retreating arm, increasing on the advancing arm to $+15^\circ$, then decreasing as the arm comes further across the torso.

The moment distribution along the arm, Figure 6, gives a fairly clear picture of the loading. At large negative pitch, where the whole length of the arm is exposed to drag forces, the moment is progressive from wrist to shoulder. This pattern is maintained, shrinking in scale, until past $+15^\circ$ pitch, after which there is a coalescence of the forearm moments and a reversal of the order along the upper arm, indicating that the forces on the upraised forearm pass above the upper gauge on the upper arm. With further study, not appropriate to the present purpose, the loading pattern may be deduced in some detail.

The in-plane moments are higher than the estimates, mainly because the latter were based on hand restraints alone, it being difficult to measure shoulder restraint on a live subject. The in-plane moment at the shoulder is not an important criterion. The value at the elbow has to be taken in conjunction with the out-of-plane moment. This is considered in the next section.

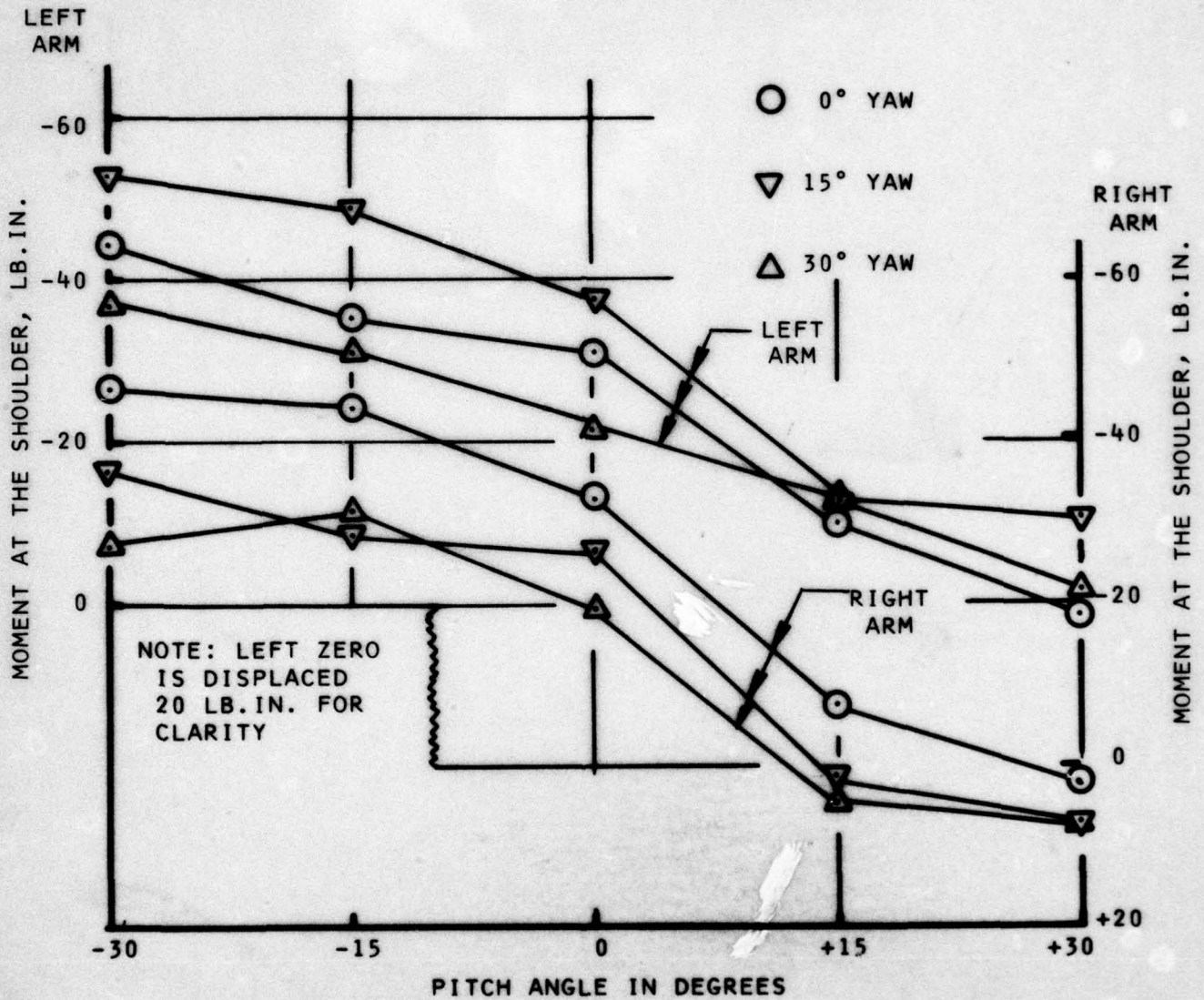


Figure 5. Variation in in-plane shoulder moments with pitch and yaw. $q = 100 \text{ lb/ft}^2$

NOTE: Moments are in (lb.in.) about the transverse axis through the shoulder, positive when tending to raise the arm.

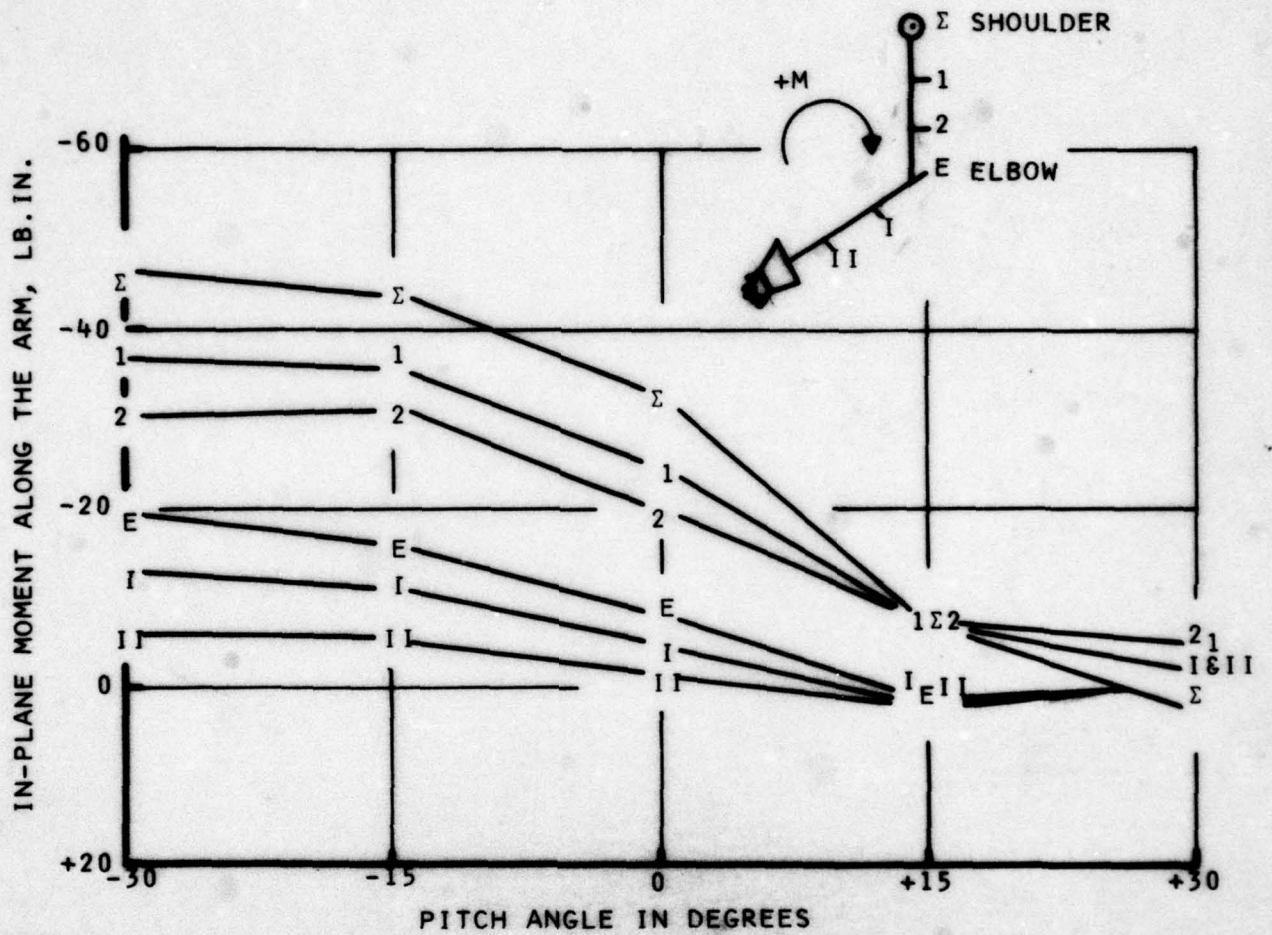


Figure 6. Distribution of in-plane moments along right arm, -30° to $+30^{\circ}$ pitch, 0° yaw. $q = 100 \text{ lb/ft}^2$

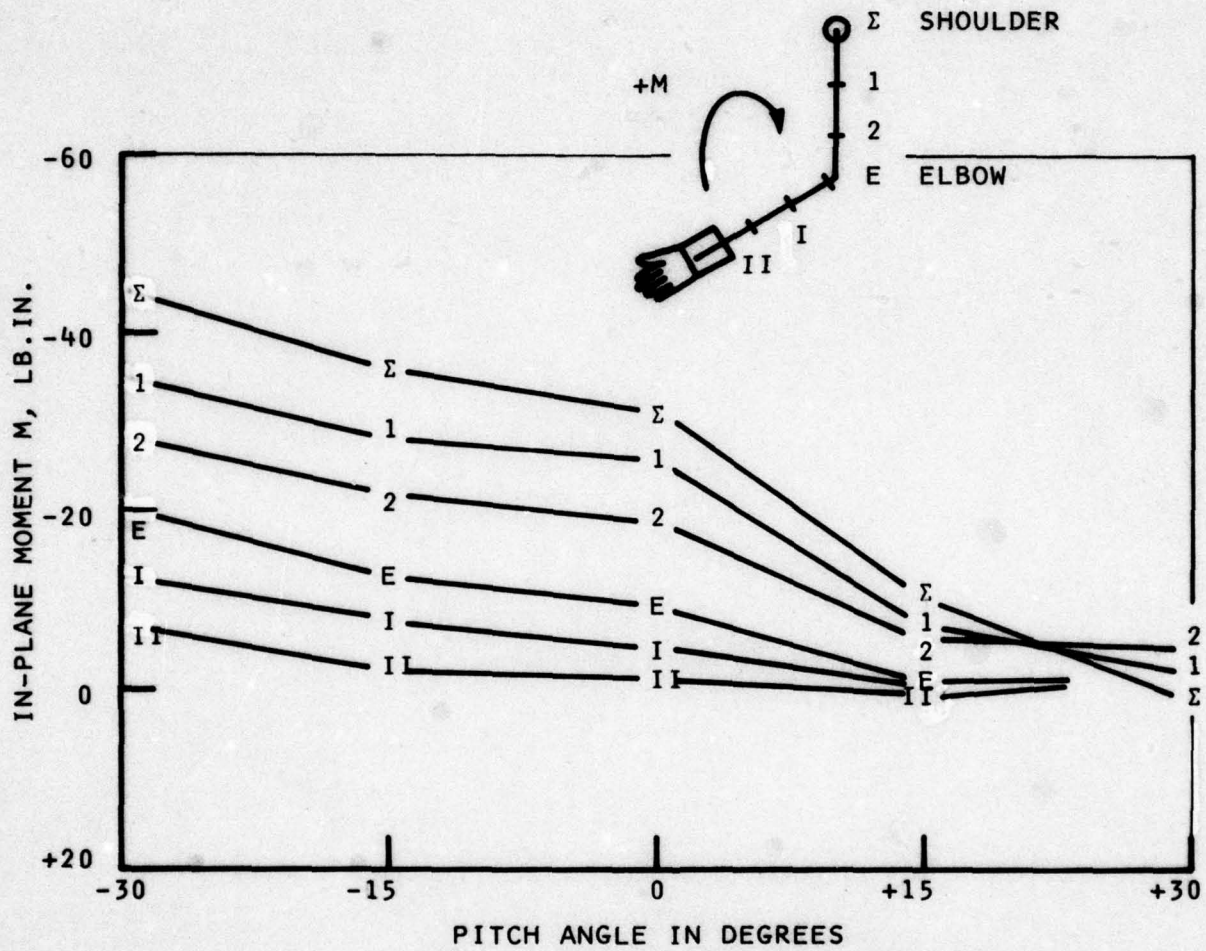


Figure 7. Distribution of in-plane moments along left arm, pitch -30° to $+30^\circ$, 0° yaw. $q = 100 \text{ lb/ft}^2$

OUT-OF-PLANE ARM MOMENTS

The out-of-plane moments, at the shoulder, like the in-plane moments, show progressive decrease with pitch over the yaw range. A curious reversal in the right arm at $+15^\circ$ may be due to gauge trouble, though the left seems to do the same to a lesser degree. The plots of distribution along the arms, Figures 9 and 10, show compatibility of left with right, though the spread is much wider on the right. Since there is only one out-of-plane direction, it should be possible to generate a line distribution of Y force which will satisfy all the values of the moments.

For comparison with the estimates of arm forces, the values of moment at shoulder and elbow are significant. A maximum of 32.7, with 19.7 in-plane, at the elbow, recorded in test 48.1, gives a resultant of 38 lb.in. at $q = 100$. Scaling to $q = 600$ gives 229, which is well within the estimate of 372 in the stress report.

At the shoulder, the joint carries a torsional moment derived from the elbow out-of-plane moment component about the axis of the upper arm. The magnitude is $38 \times \cosine 30^\circ$; approximately 33 lb.in. Thus, from the 48.1 test data, $(L,M,N) = (73.1,48.5,33)$ giving a resultant of L and N of 80 lb.in. equivalent to 480 at $q = 600$. The stress estimate was 608.

The M moment alone gives no criterion at the joint. In bending of the limbs, it is always associated with the in-plane moment and the torsion and when the maximum shear criterion is applied, it is an advantage to have the in-plane and out-of-plane moments more nearly equal than the stress report values. As for the resultant direct stress due to flexure, the over-estimate of out-of-plane moments more than outweighs the underestimate of the in-plane moment and the margin of safety is improved accordingly.

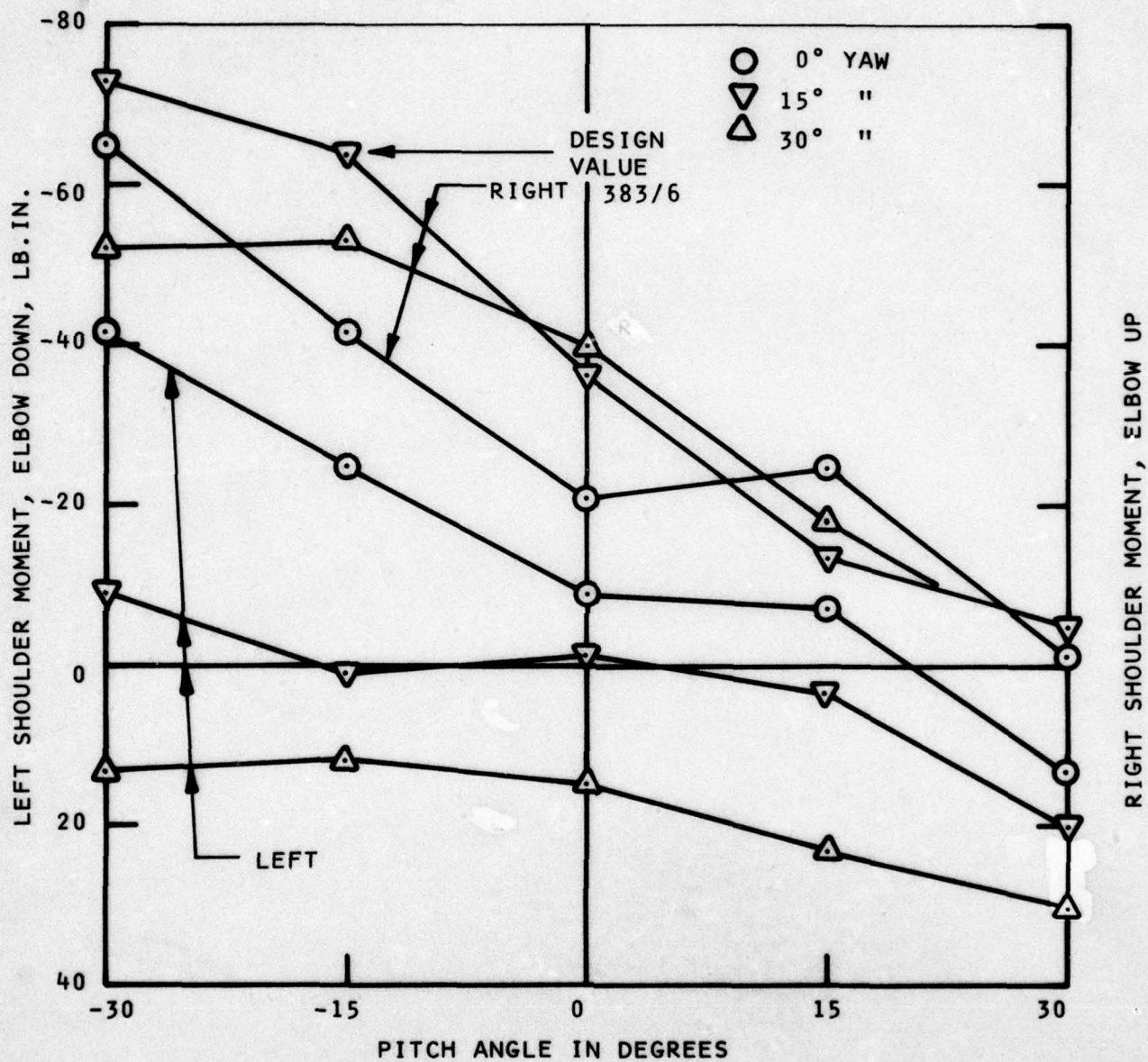


Figure 8. Variation in out-of-plane shoulder moments with pitch and yaw.

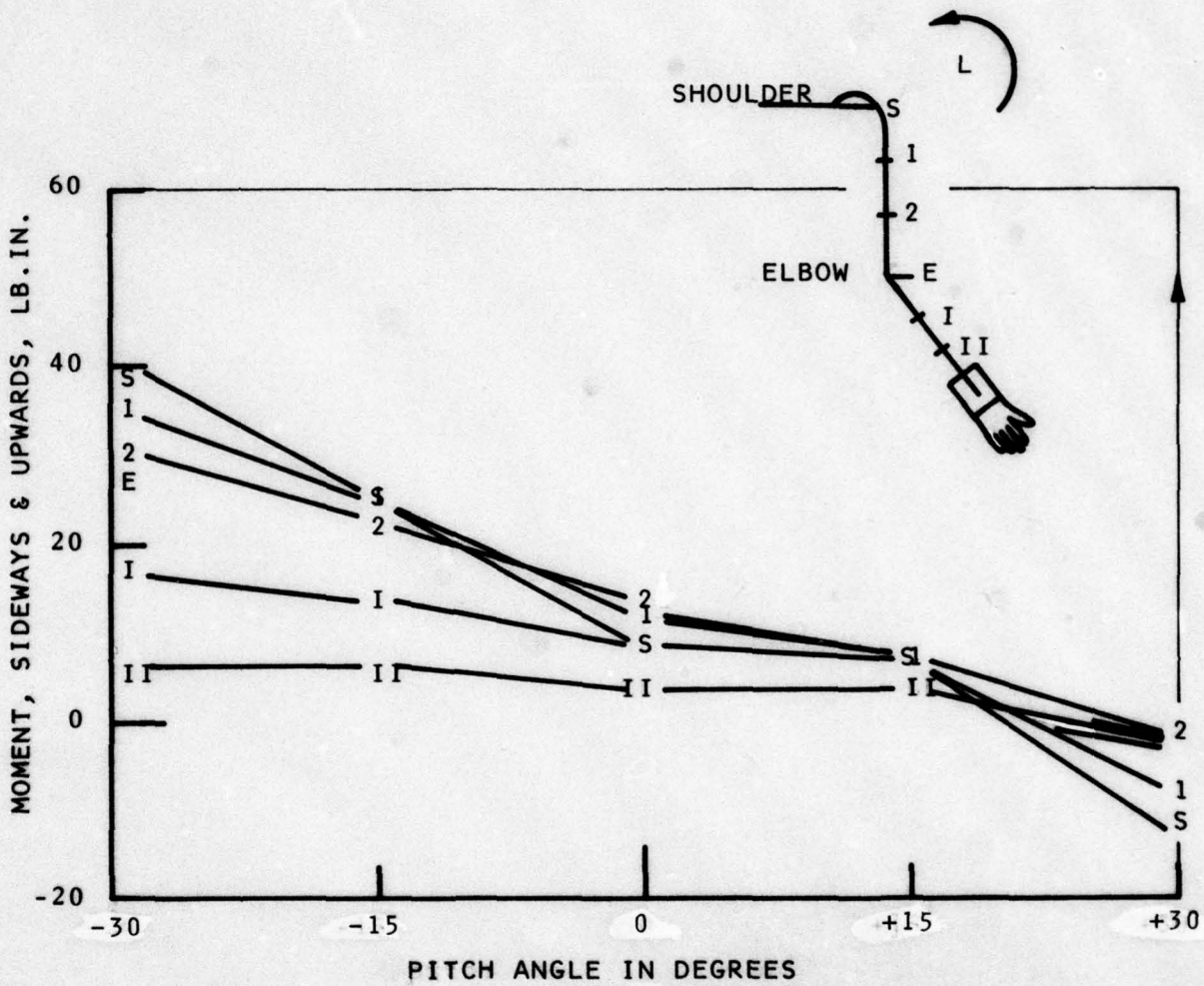


Figure 9. Distribution of out-of-plane moments along left arm, -30° to $+30^\circ$ pitch, 0° yaw. $q = 100 \text{ lb/ft}^2$

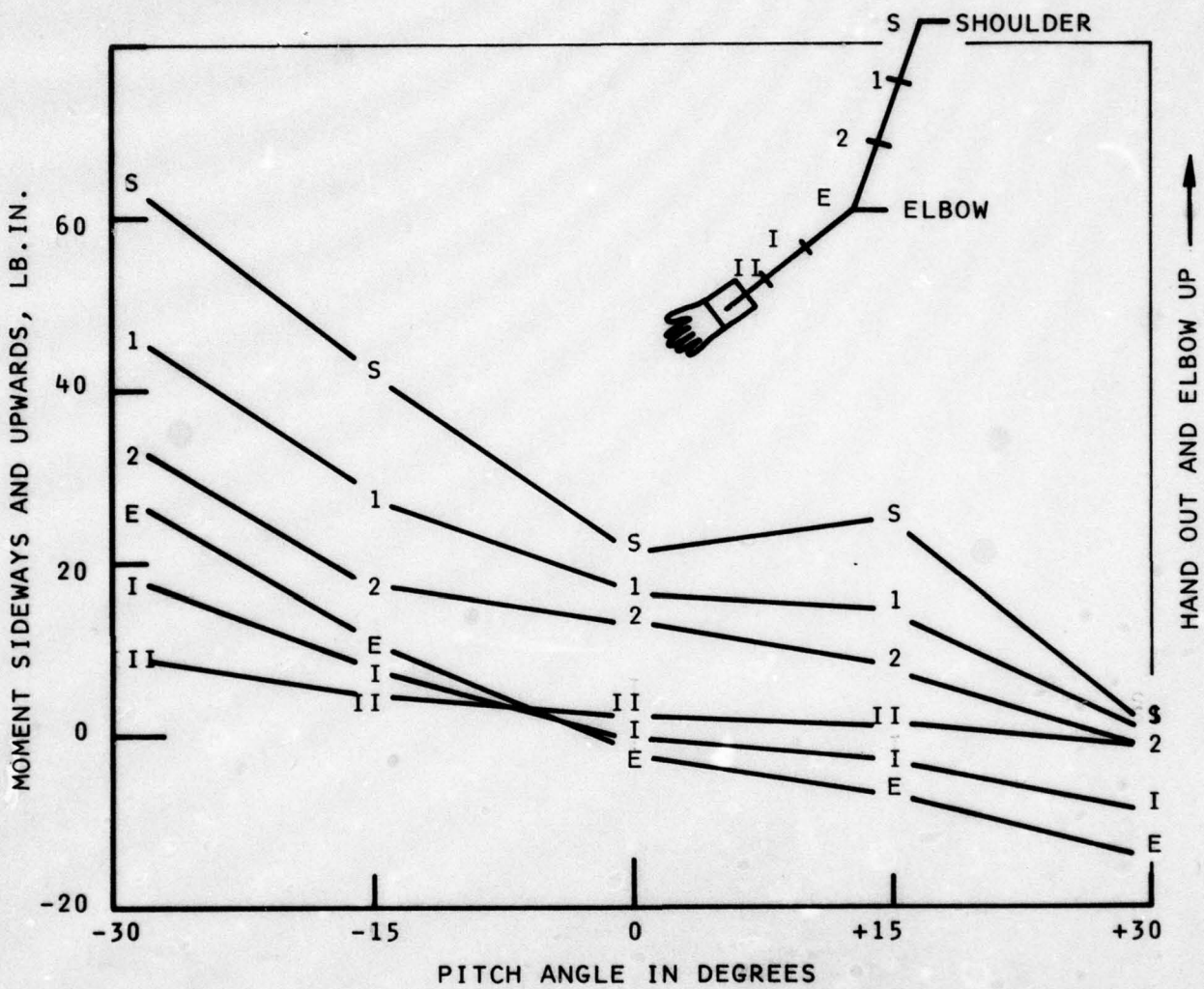


Figure 10. Distribution of out-of-plane moments along right arm, -30° to $+30^\circ$ pitch, 0° yaw. $q = 100 \text{ lb/ft}^2$

IN-PLANE LEG MOMENTS

AEDC plots of the hip moment and the related force FHZR show a large change between Mach 0.2 and Mach 0.6. A large zero shift for the upper femur gauge during calibration is reported.

A plot of the right upper leg gauge reading (Figure 11) for the sequence 47.1 through 49.5 shows an unduly big change between 47.2 and 47.3. Thereafter, the plot follows the profile of the lower gauge reading, but is about 40 lb.in. less in absolute value. This difference, if real, must mean a large negative Z force located somewhere behind the hip, which is hardly credible. However, if we assume that the gauge had a wandering zero which gave an initial error of around 80 which diminished to around 40 after the first reading, the readings come close to those of the lower gauge and the plot (Figure 11) over the pitch and yaw range, resembles that for the left leg, (Figure 12).

The moments along the left leg at 0° yaw, Figure 13, shows a big increase in (negative) value between lower leg and hip at -30° pitch. This progressively decreases as the pitch increases. The moment at the knee is practically constant between -30° and 0° pitch and diminishes steadily to +30°. The upper leg moments are equal at about +4° pitch and reverse their order and sense at higher pitch angles while the lower leg moments retain their original order and sense. This is consistent with the concept of a predominant rearwards force (X) due to drag, decreasing in magnitude, but changing little in direction as the bent leg rotates in pitch. (The three lower gauges of the right leg may be added to this plot in order to confirm the essential similarity between the two legs at zero yaw.)

As in the case of the arm, the in-plane estimates for the leg were low and for a similar reason. Likewise, the in- and out-of-plane loads in combination determine the stress criteria. These are discussed in the next section.

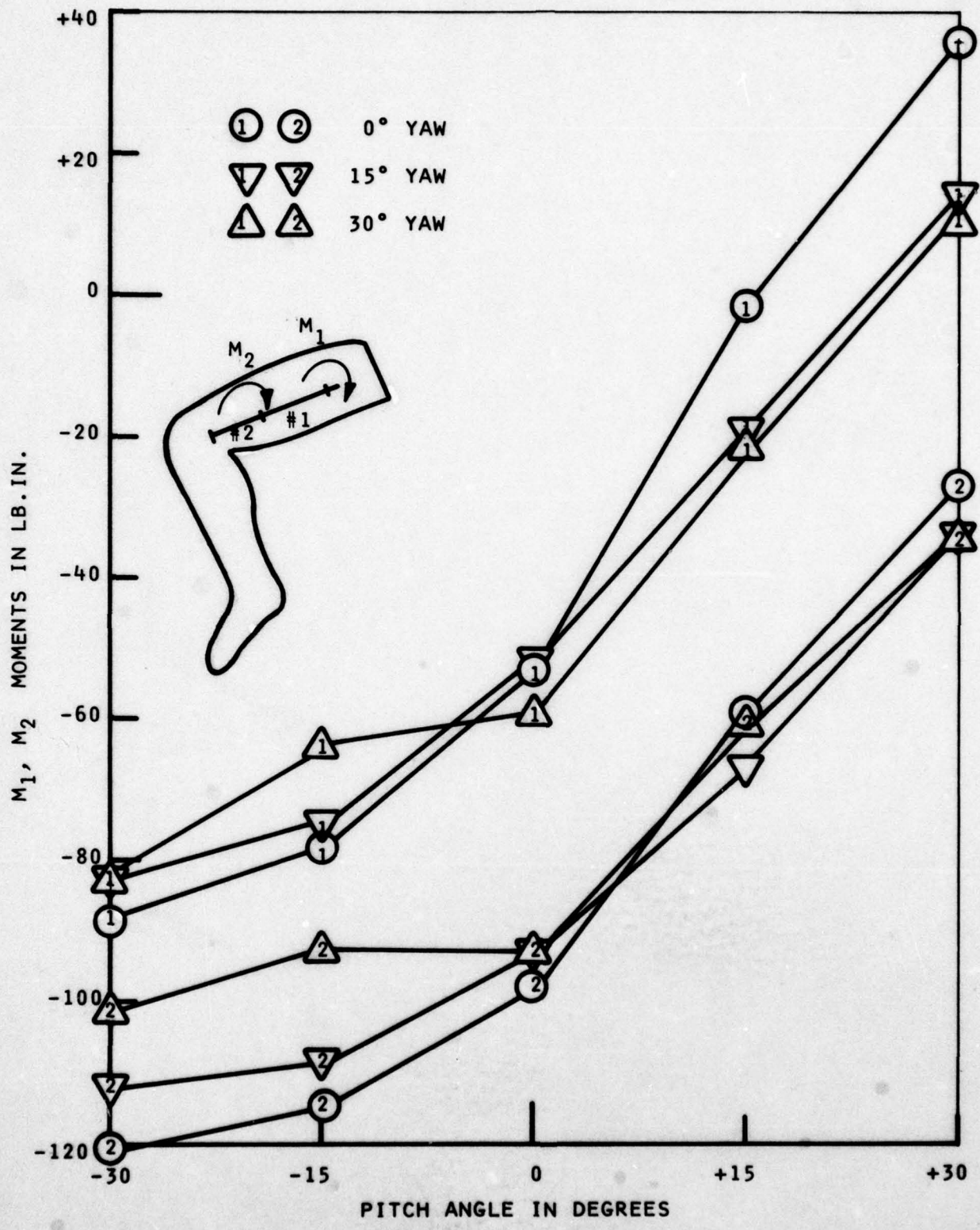


Figure 11. In-plane moments at right upper leg gauges in yaw to right.
 $q = 100 \text{ lb/ft}^2$

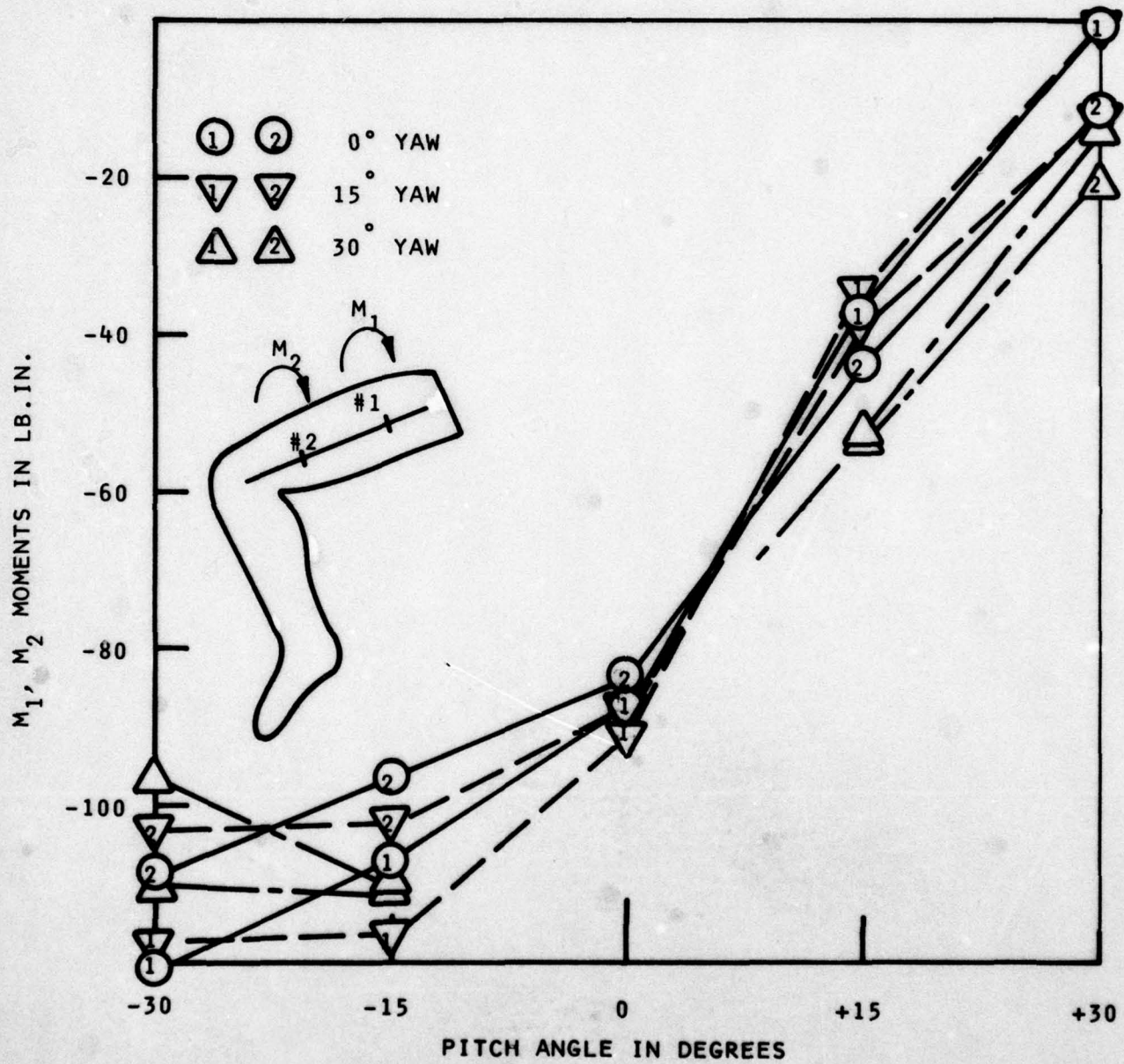


Figure 12. In-plane moments at left upper leg gauges in yaw to right.
 $q = 100 \text{ lb/ft}^2$

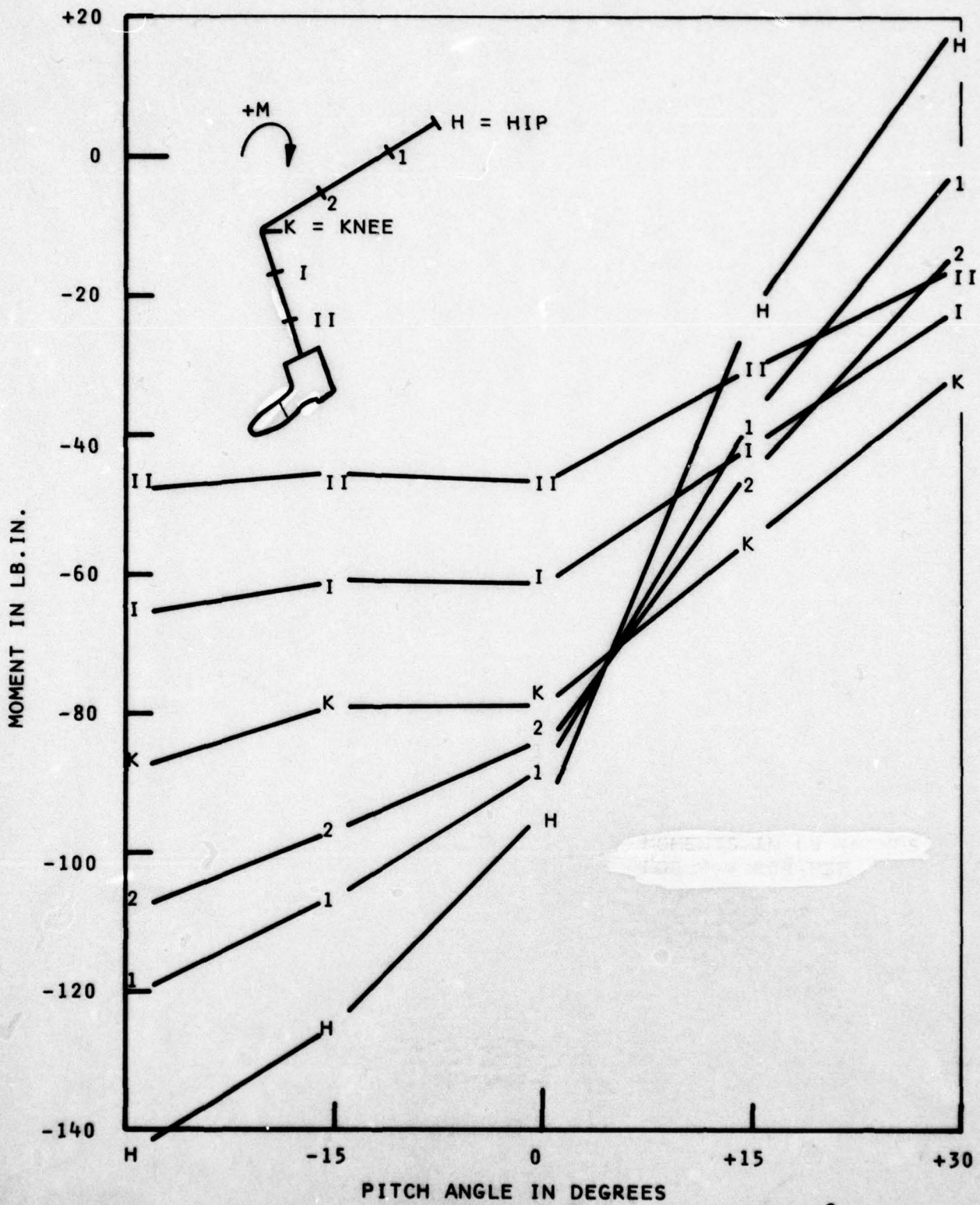


Figure 13. In-plane moments along the left leg. $q = 100 \text{ lb/ft}^2$

OUT-OF-PLANE LEG MOMENTS

The Y direction forces are outwards on each leg, except possibly on the left leg in yaw to the right. Figure 14 shows the variation over both legs in yaw to the right (with the left scale inverted). It shows clearly that the left and right legs are closely matched at zero yaw, and, except for a curious value at data point 49.4, present no surprises.

The distribution along the legs at zero yaw (Figures 15 and 16) shows close agreement between left and right and, very clearly, that nearly all the side force is in the vicinity of the knee. The small loads on the lower leg actually are reversed on the left leg throughout, and on the right when pitched nose up. A similar plot for the right leg at 30° yaw (Figure 17) tells a different story. Here there is considerable loading on the outer leg. The effect of the knee being bent past 90° shows in the overlap of the lower leg moments past #2 upper leg gauge.

For comparison with the stress analysis values, the knee moments in- and out-of-plane have a resultant $(63 + 81) = 103$, equivalent to 618 at $q = 600$. The stress report used 638 (with an M.S. of 0.82). This case is adequately covered. Taking the knee moment unabated as a torque in the upper leg is also adequately covered in the analysis by the value 685.

The hip moment, 144 lb.in., is covered by the N_H value 924 lb.in., used in the stress analysis, since $924/6 = 154$, with handsome safety margins as well. The tightest margin comes in meeting the AEDC requirement for the hip joint preload. The applied moment (L_H, N_H) gave a margin 0.23. The test data value, combining the moments with the out-of-plane hip moment, is $(80.9, 144) = 165$ lb.in. The stress report used 1203, equivalent to 200 at $q = 100$ and this covers the case.

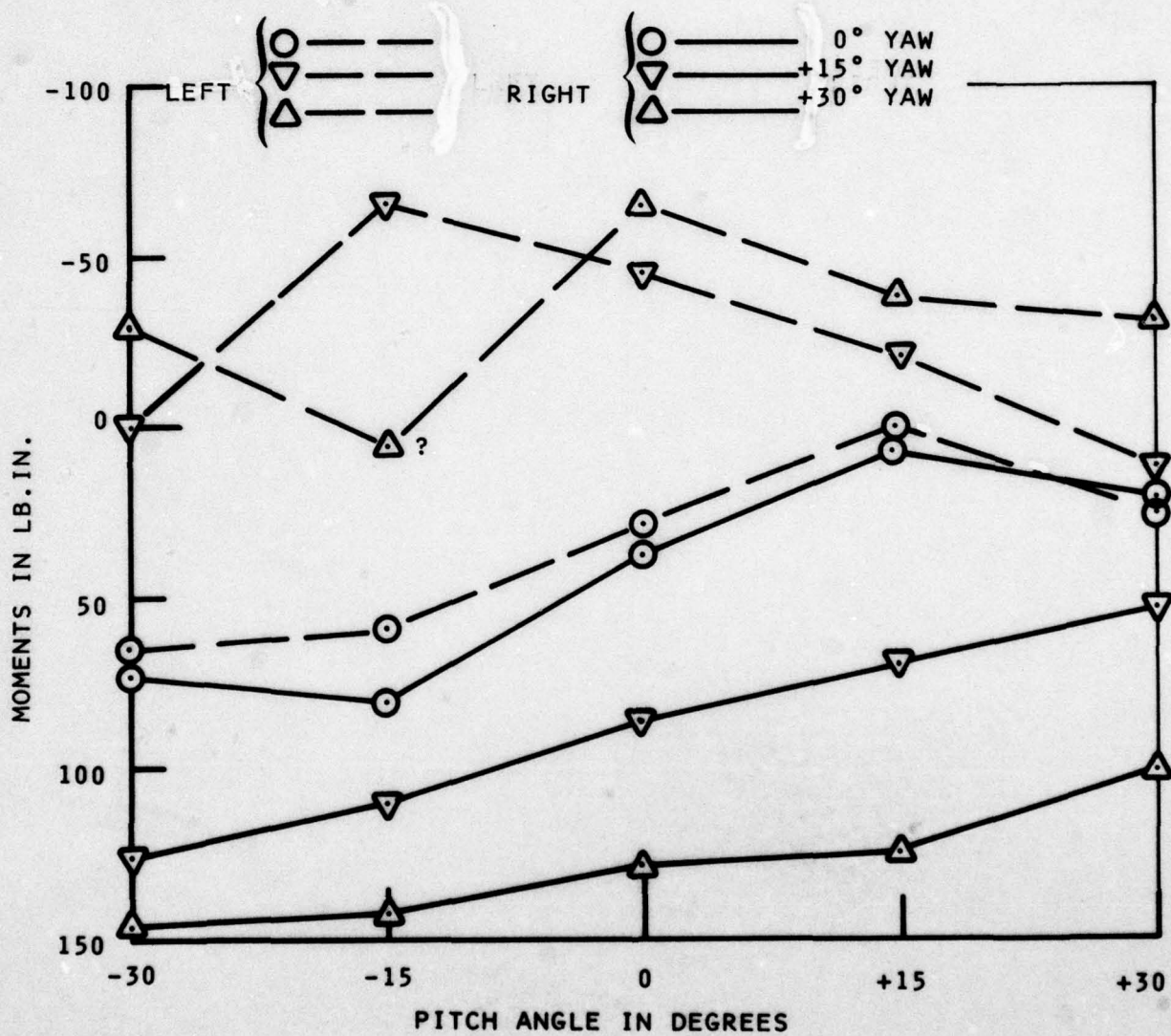


Figure 14. Out-of-plane leg moments vs. pitch and yaw. $q = 100 \text{ lb/ft}^2$

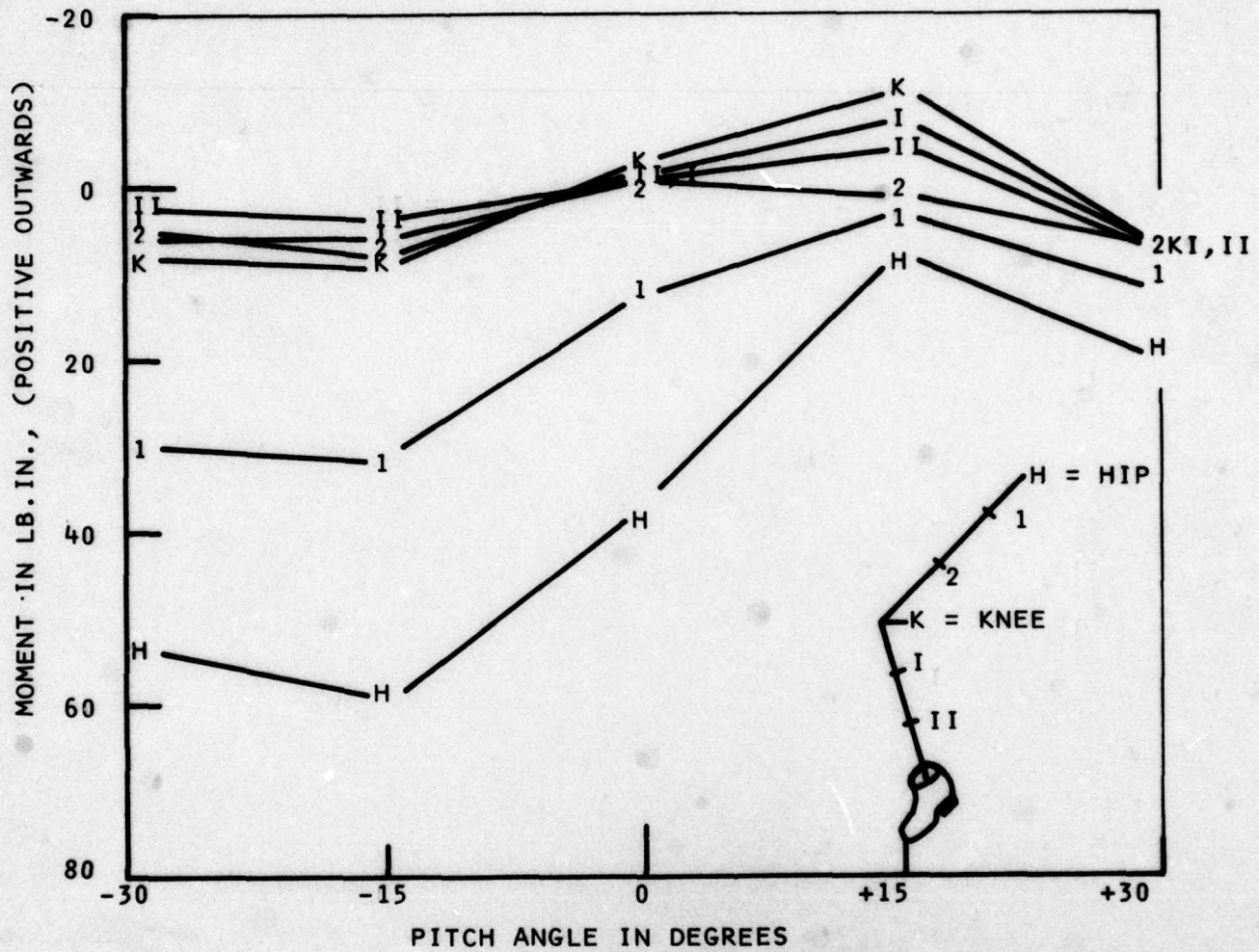


Figure 15. Distribution of out-of-plane moments along right leg at 0° yaw.
 $q = 100 \text{ lb/ft}^2$

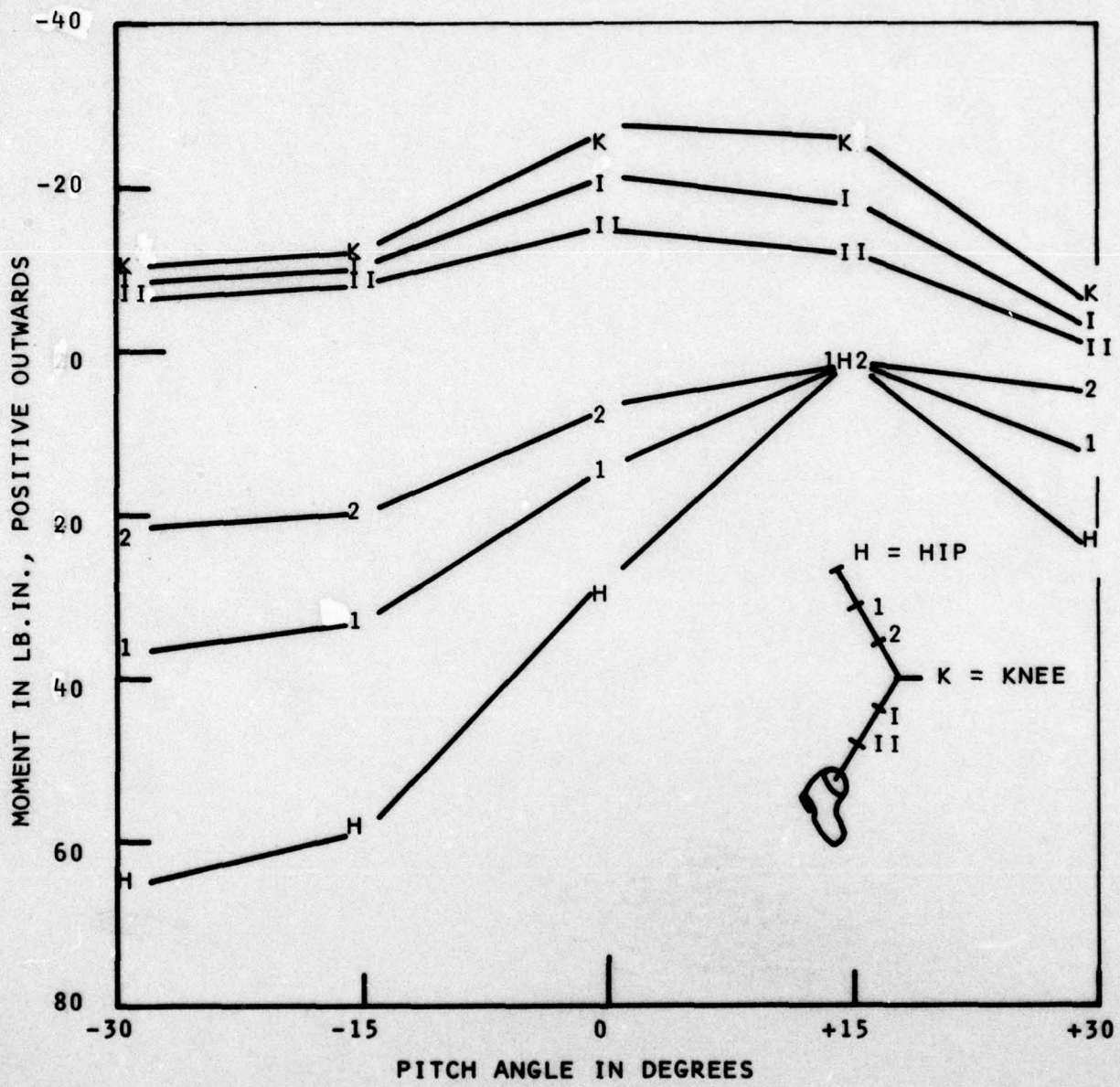


Figure 16. Distribution of out-of-plane moments along left leg at 0° yaw.

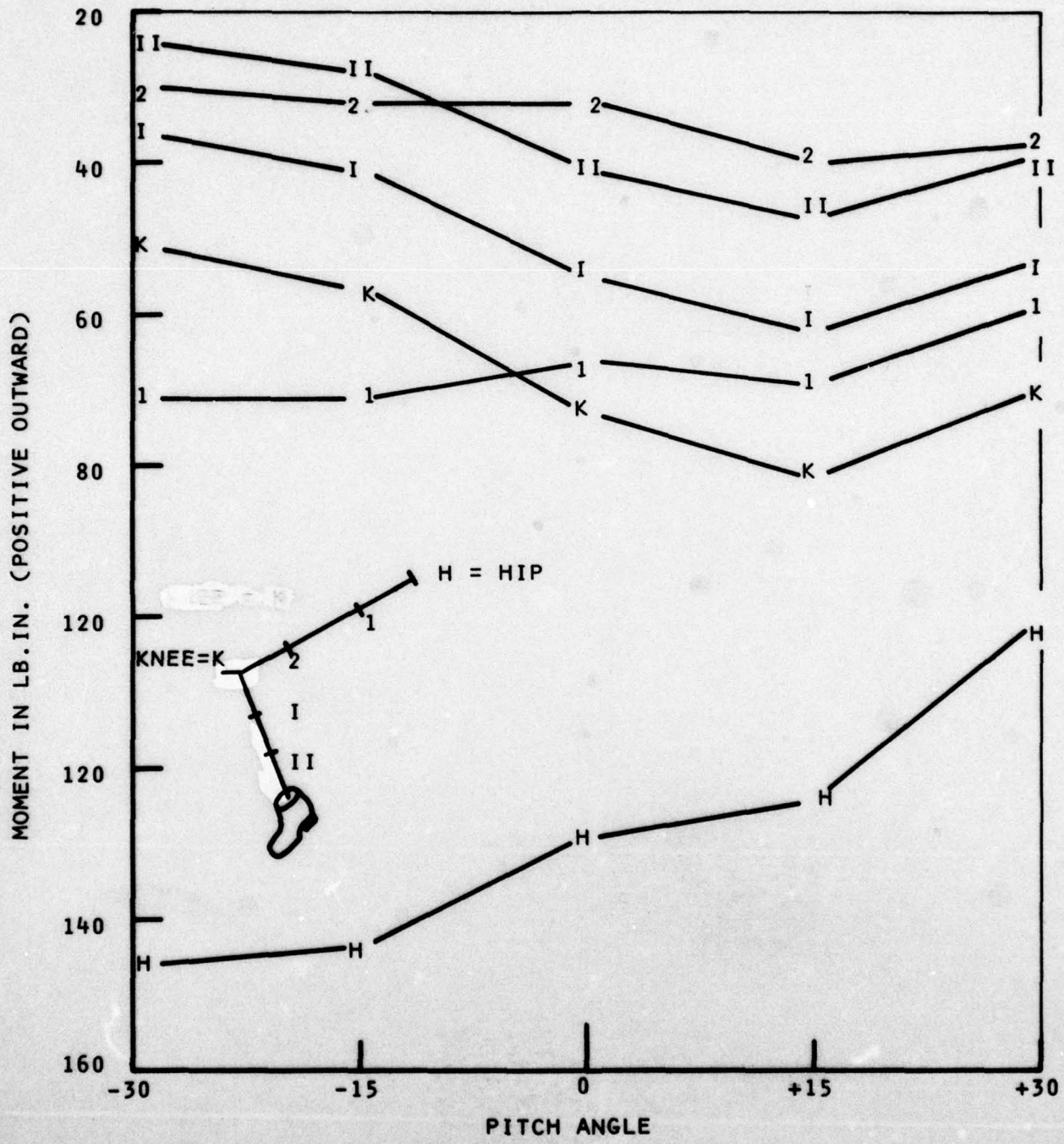


Figure 17. Out-of-plane right leg moments distribution at 30° yaw.

CHANGES WITH MACH NUMBER

It was noted in the section on overall forces and moments that the overall force on the model increased approximately 30% between Mach 0.5 and Mach 1.4, at the same q value.

Searching through the data for maximum values of elbow and shoulder moments yields the data plotted in Figure 18. These maxima occur at large negative pitch when the limb presents the greatest frontal area to the airstream. The rise between Mach 0.5 and Mach 1.4 is just under 25%. (The corresponding rise in (actual/nominal) dynamic pressure is a little over 50%.)

It is assumed that a similar rise occurs in the leg moments. We, therefore, consider that the maximum loads across the board are adequately covered if, using the loads from Mach 0.5, we can maintain a safety margin of 0.25.

Table 1 shows that this is, in fact, possible. Reference should be made to the original document because the quotable stress in a member is not necessarily in direct ratio to the applied moment. The shear has to be considered too.

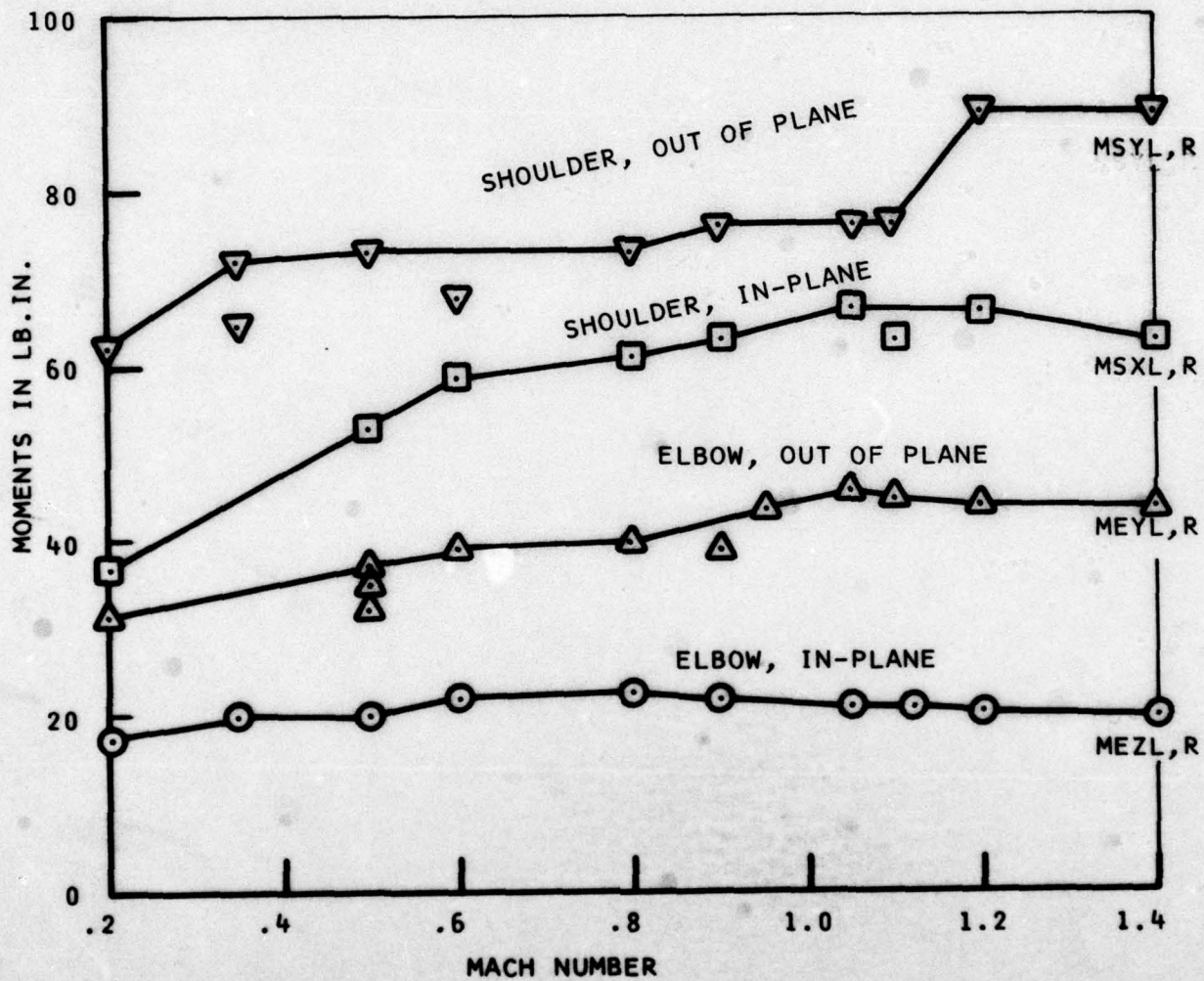


Figure 18. Increase in shoulder and elbow moments with Mach number.

Table 1. Maximum Values and Comparison with Design Estimates

<u>Stress Topic</u>	<u>Reference</u>	<u>Quoted M.S.</u>	<u>Data Max./Est.</u>	<u>New M.S.</u>
Shoulder joint bolt preload	2.3, p.20	0.09	480 / 608	0.38
Upper arm Maximum shear	2.3, p.21	0.75	1679 / 4375	Ample
Elbow lug	2.3, p.22	1.38	229 / 372	2.87
Elbow spigot	2.3, p.23	0.84	229 / 372	1.98
Forearm	2.3, p.23	0.06	229 / 372	0.72
Hip joint bolt preload	2.4, p.25	0.23	165 × 6 / 1203	0.49
Upper leg	2.4, p.26	1.08*	165 × 6 / 1203	1.52
Knee joint	2.4, p.27	0.82	618 / 638	0.88
Lower leg	2.4, p.28	0.044	517 / 638 **	0.28

* Adjusted for round section, as built.

** The test data moment is due to a larger force with center of pressure nearer the knee. Hence a more rapid reduction in moment as we move away from the knee.

ALTERNATING LOADS

The test data contains no information on alternating loads.

Once it has been established that maximum stress (alternating plus steady) is less than one third of the material yield, the possibility of failure by fatigue recedes beyond 10^8 cycles and may be dismissed from further consideration. In this context, stress means the actual stress occurring locally at the point where failure might originate, and not the nominal stress (like $P/A + M/Z$) used in conventional analysis. At levels well below the yield, the local stress may be taken as the nominal (principal) stress multiplied by a suitable "notch factor" or stress raiser. In good structural design, these factors are small.

In the limbs of the model crewman, the most likely sites for fatigue failure are the elbow and knee joints, since these feature intricate machining, keyways, and some rather tight corners, which may be awarded a notch factor of 2, possibly. At these locations, the safety margin under the maximum steady loads, referred to one third yield for the material, is close to zero. If at these extremes, an appreciable alternating component is encountered, then fatigue failure at 10^{6-7} cycles emerges as a possibility. This means 1 to 10 days at 10 Hz., sustained operation. Since there is no intention of staying on maximum load for such periods, and since the mean load is far less than the maximum, it seems unlikely that we have a fatigue problem. However, to be more precise, it is necessary to have information on frequency, amplitude, and association with steady loads.

CONCLUSIONS

The measurements make good sense and present a clear and convincing picture of what was happening in the tunnel. Specific conclusions are as follows:

- (1) The neck pillar broke under quite moderate loads because it was weak in torsion. Its strength in bending, though not sufficient to meet AEDC requirements at $q = 600$ psf, was adequate at the test $q = 190$ psf at failure. The possibility that the loading might be offset from the axis of the member had apparently been overlooked by its designers, Precision Force Measurements, Inc.
- (2) The estimated loads used in our stress analysis were generally greater than the maxima encountered experimentally, when ratioed to the same q value. Estimates of rearwards forces derived from hand and foot restraints on live subjects were low, but when compounded with sideways loading, give stress criteria not less than those yielded by the data. Therefore, the stress analysis is considered to be valid as it stands.
- (3) The data is of high quality, is self-consistent and largely self-explanatory. It is very copious; we have so far scrutinized only a small fraction of it. One gauge failure is identified; there are no big surprises. The results seem to be qualitatively as expected and accurate, if the calibration is accepted.

These conclusions are reached after a study of runs 25, 47, 48, 49 (at Mach 0.5) in some detail. Tests at higher Mach numbers have been scanned for larger values of the maximum loads. Generally, although total drag increases by nearly 40%, there appears to be little change in limb loading with Mach number; typically less than 25% increase. This is apparent from the AEDC plots and can be confirmed from the tabulated data. The measured increase in loads is in excellent agreement with predictions made in our Proposal No. 101 (22 April 1971) where we pointed out that, due to the detached bow shock, force increases should be significantly less (about half) than those inferable from the dynamic pressure relationship

$$\frac{q}{q_0} = 1 + \frac{M^2}{4} + \frac{M^4}{40} + \dots$$

Assuming that the model as built conforms to the drawings with proper quality of fabrication, and that it has not been damaged by mishandling other than the legitimate testing, there appears to be no reason why it should not be structurally adequate to complete any further test schedule at maximum tunnel pressure within the specified attitude ranges.

EPILOGUE

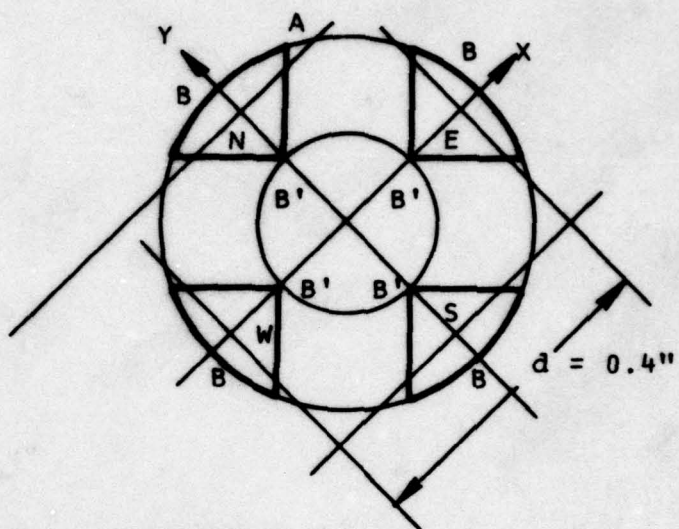
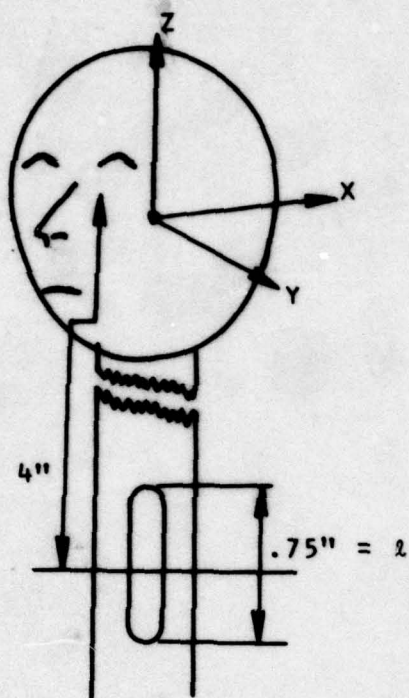
This report, in essentially the same form as it now appears, was put out as a working paper in July 1978 for the explicit purpose of showing why the model should be satisfactory for further use in tests in which a model simulating the F-16 aircraft forebody was mounted on the crewman support sting so as to enclose him initially and to slide away downwards and forwards from him to simulate the relative positioning during ejection.

For these tests a new load-measuring neck pillar was made. Though less sensitive than the earlier one, it had ample reserve of strength and the tests were concluded without untoward incident. The results of these tests are now available as tabulated data from AEDC.*

*Reichenau, D.E.A., "Aerodynamic Characteristics of a 0.5-scale Crewman/Ejection Seat Model During a Simulated Ejection from an F-16 Fighter at Freestream Mach Numbers from 0.4 to 1.2." AEDC-TSR-78-P42, September 1978.

APPENDIX

NECK PILLAR - STRESS ANALYSIS



SECTION CHARACTERISTICS

From PMI, Inc. Analysis

$$\left\{ \begin{array}{l} A = .0117 \text{ in}^2 \text{ per leg} \\ I_{NA} (y_1 y_2) = 1.74 \times 10^{-5} (.05, .075) \text{ per leg} \\ I_{BB} (y_1 y_2) = 0.937 \times 10^{-5} (.094, .094) \text{ per leg} \end{array} \right.$$

Stresses Due to X Moment

$$M_x = X \cdot 4.0 \text{ lb.in.}$$

Moment is transferred by (i) M_1 as differential end load in EW legs

$$M_x = M_1 + M_2 \quad \text{(ii) } M_2 \text{ as bending of all legs}$$

End load stress due to $M_1 = \pm M_1 / Ad$

Tilt angle $\alpha = 2M_1 l / Ad^2 E$

All legs tilt same angle, thus absorbing $M_2 = E \Sigma I x / l$, where $\Sigma I = 2(I_{NA} + I_{BB}) = 5.354 \times 10^{-5}$

Substituting for α ,
$$M_2 = \frac{E \Sigma I}{l} \frac{2M_1 l}{Ad^2 E} \text{ so } M_x = M_1 (1 + 2 \Sigma I / Ad^2)$$

Inserting numerical values

$$M_x = M_1 (1 + .057), \quad M_1 = .946 M_x$$

$$M_2 = .054 M_x$$

Then end load stress in E,W due to M_x

$$f_{M_x(EW)} = \pm .946 M_x / Ad = \pm \underline{808 X}$$

Bending stress in N,S due to M_x

$$f'_{M_x(NS)} = .054 M_x \frac{I_{BB}}{\Sigma I} (y_1 y_2 / I)_{BB}$$

$$= \underline{379 X}$$

Bending stress in E,W due to M_x

$$f'_{M_x(EW)} = .054 M_x \frac{I_{NA}}{\Sigma I} (y_1 y_2 / I)_{NA}$$

$$= \underline{202 X} \text{ and } \underline{303 X}$$

Shear Transfer (X)

All legs deflect same, inflexion at mid point

Max bending at ends

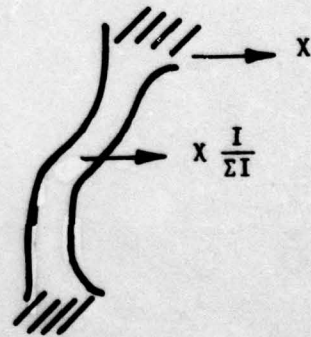
Each leg takes $(I/\Sigma I) \cdot X$

Then max stress at ends = $\frac{Xl}{2} \frac{I}{\Sigma I} (y/I)_{NA} \text{ or } BB$

So

$$f_x(NS) = X \cdot \frac{75}{2} \cdot \frac{10^5}{5.354} \cdot .094 = \underline{658 X}$$

$$f_x(EW) = \underline{350 X} \text{ or } \underline{525 X}$$



Torsion Due to Offset Loading

If X is offset by an amount δ_x , a torque $X\delta_x$ is transmitted by the neck pillar.

$$\text{Then } X\delta_x = Q_x = Q_1 + Q_2$$

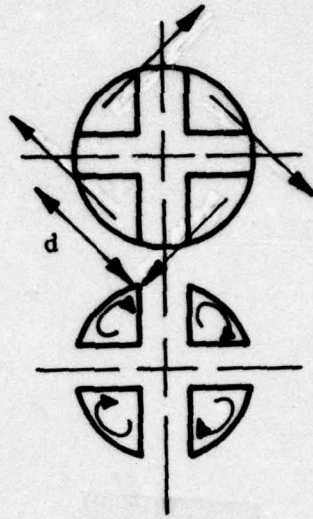
where Q_1 is transmitted by cyclic shears, and

Q_2 by the legs individually.

$$\text{Then, shear force per leg} = Q_1/2d$$

$$\text{Leg deflection (Roark, p. 104)} = \frac{2}{3} \frac{Q_1}{2d} \frac{(\ell/2)^3}{EI_{BB}}$$

$$\begin{aligned} \text{Angle of twist } \theta &= \text{deflection}/(d/2) \\ &= \frac{2}{3} \frac{Q_1}{d^2} \frac{\ell^3/8}{EI_{BB}} = \frac{Q_1}{E} \cdot 12,628 \end{aligned}$$



Torsional stiffness of each leg gives

$$\begin{aligned} \theta &= \frac{Q_2}{4} (\ell/KG) & \text{where } K &= .0825(.125)^4 \\ & & & \text{(Roark, p. 199)} \\ &= \frac{Q_2}{G} (9309) \end{aligned}$$

$$\frac{Q_1}{Q_2} = \frac{9,309}{12,628} \frac{E}{G} = 2.69$$

$$Q_1 = .73 Q_x \quad \text{and} \quad Q_2 = .27 Q_x$$

The direct stress in all legs due to Q_x is

$$\begin{aligned} f_{Q_x} &= 0.73 Q_x (y/I)_{BB} \\ &= 0.73 X\delta_x \\ &= 3944 (X\delta_x) \end{aligned}$$

$$\text{With } \delta_x = 0.5/\delta_2$$

$$f_{Q_x} = \underline{1394 X}$$

Summation of Stresses in the Legs

Direct stresses at the same location are additive.

<u>Location</u>	<u>Due to X</u>	<u>Due to Y</u>
N,S (NA)	--	$f_{my} + f'_{my} + f_Y$
N,S (BB)	$f'_{m_x} + f_x + f_{Q_x}$	$f_{my} + f_{Qy}$
E,W (NA)	$f_{mx} + f'_{mx} + f_x$	--
E,W (BB)	$f_{mx} + f_{Q_x}$	$f'_{my} + f_Y + f_{Qy}$

Maximum values with $X = Y = 45$ and $\sqrt{\delta_x^2 + \delta_y^2} = 0.5$

$$f_{CT}(NA) = (808 + 303 + 525)X$$

$$= \underline{73,620 \text{ psi}}$$

$$f_{CT}(BB) = (808 + 379 + 658 + 1394)X$$

$$= 1845 X \text{ without offset load}$$

$$= 3239 X \text{ with offset load,}$$

that is,

$$f(BB) = \underline{83,000} \text{ without offset,}$$

$$\text{or } \underline{145,800} \text{ with offset} \quad \text{MS - Negative}$$

Direct load due to upward load (Z) at 60 lb. will increase tension by 1300 psi.

Shears due to torsion in legs not included.