DEVELOPMENT OF THE LEARJET 28/29 WING USING NASTRAN ANALYSIS

Robert R. Boroughs
Gates Learjet Corporation

SUMMARY

A great deal of the structural development work performed on the Learjet 28/29 wing was accomplished using Nastran analysis. This included the basic sizing of primary structural members such as wing skins, wing skin splices, and spar caps, as well as the calculation of preliminary weight estimates utilizing the weight computation routine in Nastran. The eight spar redundancy of the Learjet wing made this task somewhat more complex and challenging than for the more determinate type wing structures. The discussion that follows describes some of the problems that were encountered and the solutions and methods that were used.

INTRODUCTION

The Learjet 28/29 wing was the most significantly different derivative wing both structurally and aerodynamically, since the introduction of the Learjet Model 23. This wing evolved from the earlier Model 35/36 wing and has been installed on a modified Model 25 fuselage. The most outwardly noticeable changes to the 28/29 wing from previous Learjet wings were at the wing tips. Here the two foot extension and tip tank on the Model 35/36 wing were replaced by a six foot extension and winglet on the 28/29 wing (see Figures 1 & 2). The outward appearance of the 28/29 wing in the inboard section remained the same as the 35/36 wing, and internally this section still had eight spars as does the 35/36, but this was where most of the similarity ended. The wing skin and center line splice plate thicknesses have increased, the section properties of several of the spar caps have increased, and wing skin stringers have been extended or added.

This same basic 28/29 wing configuration was later selected as the airfoil for the Learjet Model 54/55/56 series aircraft. Some growth capability was included in the 28/29 wing for the 50 series aircraft, but the complete detail structural definition was to be determined further into the 50 series project.

BACKGROUND

Approval to proceed with the development of the Learjet 28/29 aircraft was received in February of 1977, and work began on the wing structural analysis using Nastran that same month. The basic objectives established for the wing structural redesign were to obtain satisfactory margins of safety, minimize the impact on tooling, keep the weight increases as small as possible, and complete the certification on a very tight schedule. These goals were to be achieved while operating under constraints such as limited manpower availability and increasing lead times for parts and materials. Factors such as these later influenced alternatives that were chosen during the course of this project.

Initial analytical work performed on the 28/29 wing inboard section was accomplished using the 35/36 Nastran wing model described in NASA TMX-3428 (Ref. 1). This model was later updated in the outboard section with the six foot extension and winglet attachment structure. Sizing of the structural members was to be accomplished by a combination of Nastran analysis, post processor programs, and detail stress analysis. Since the results of the 35/36 Nastran wing model had correlated very closely with the experimental data from the 35/36 wing static test, the strategy for the 28/29 wing qualification was to perform limit load tests on a highly instrumented wing static test article, establish a correlation between the Nastran results and experimental data at this point, and qualify the ultimate load conditions by analysis using Nastran results for FAA certification. The advantage of this type of approach was to reduce the costs and lead time associated with a static test.

MODEL DESCRIPTION

Since the 28/29 wing was symmetrical about the aircraft center line, a half model was used. The Nastran wing model geometry was developed from the 35/36 wing contours inboard of W.S. 181.10 and from the 28/29 wing contours outboard of W.S. 181.10. The wing surface was divided into a basic mesh which was defined by the intersection of the spar caps and rib caps. This was further subdivided in the spanwise direction by breaking these bays into equal increments where possible. Structural members modeled included the spar caps, rib caps, and wing skin stringers with ROD elements, the spar webs and shear webs with SHEAR elements, and the wing skins and wing skin splices with QDMEM2 elements (See Ref. 2).

Modeling of the wing skins included the effect of sculpturing and contouring, and the lower skin reflected the stiffness of the access doors. The wing skin stringers were modeled by dividing the stringer areas in half and lumping each half as a separate element with the adjacent spar cap. This was done in order to simplify the modeling and conserve degrees of freedom. There were four different splice plates on the 28/29 wing skin. These were the upper and lower splices at W.S.0.00 and the upper and lower splices at W.S.181.10 where the six foot wing extension was attached. The finite element representation reflected the contour and taper characteristics that had been machined into these members.

The six foot extension geometry was basically an extension of the taper and contour of the inboardwing section. The inboard eight spars were continued into the six foot extension, and two additional spars were added in the trailing edge. This spar addition was incorporated to provide stiffness and an internal load path for forces developed by the winglet, since the winglet was mounted very near the trailing edge of the wing. The winglet attachment structure was modeled from W.S. 244.10 to winglet station 6.00. This structure included spars five through ten and the winglet skin in this area. ROD elements were used to model the winglet spar caps, SHEAR elements were used to model the winglet spar webs, and QDMEM2 elements were used to model the winglet skin. Beyond winglet station 6.00 the winglet structure was modeled strictly as a load fixture using Nastran BAR elements (See Fig. 3).

Constraints for the model were applied in the spanwise direction at the W.S.0.00 spar caps, and in the vertical direction at the wing attachment fittings at spars 2, 5, 7 and 8, and in the fore-aft direction at spar 5. Ten basic load conditions were examined during the static analysis. These cases consisted of positive and negative gust loads as well as various landing loads.

STRUCTURAL CONFIGURATION DEFINITION

Preliminary design analysis of the existing 35/36 wing structure had revealed that larger section properties or higher allowables would be necessary to sustain the increased 28/29 loads. During the initial phase of wing redesign strong emphasis was placed on retention and utilization of existing tooling. This was done in an attempt to keep tooling costs and the parts count down and simplify the fabrication and assembly process. Consequently, several different configurations were analyzed where the wing skin was selected as the primary member for material addition with reinforcement of the spar caps in localized areas as the secondary means of material addition. This type of approach normally has been reserved to supersonic airfoil construction where a thin wing chord section eliminates many possible structural configurations (See Ref. 3), but in this situation the constraints were more cost oriented.

Each successive configuration examined had a thicker skin than the preceding configuration, but many of the spar caps still had unacceptably high stress levels. By this time the weight increases had become substantial and the impact of this parameter on flight performance had become a serious factor. Consequently, this approach was eliminated as an acceptable solution for obtaining the basic design goals.

A new approach was then chosen where the emphasis was placed on increasing the spar cap areas in combination with the wing skin thickness as the means for developing satisfactory stress levels. Based on the wing skin studies that were conducted earlier, a wing skin configuration was selected for the 28/29 wing. The thickness of these skins were slightly greater than the existing 35/36 wing skins, but the total thickness was also considerably less than most of the other configurations previously examined. The material selected for both the upper surface and lower surface was 2014-T6. This was the same material that had been used on the upper surface of the 35/36 wing, but on the lower surface the 2014-T6 was used in place of 2024-T3. Selection of this material was influenced to a great extent by raw stock lead times in effect during that period, as well as the change in loads from the 35/36 wing to the 28/29 wing.

Using the basic wing skin selected from the previous studies, spar cap areas were increased in the regions where the margins of safety were deficient. This process initially concentrated on the wing section inboard of the landing gear rib where the stresses were the highest. When this region was improved to satisfactory levels, the process was expanded to the region outboard of the landing gear rib, and from there on out to the winglet attachment structure.

A localized buckling analysis which has been described in NASA TMX-3428 (Ref. 1) was used to determine the non-linear effect of wing skin buckling on the spar cap stresses. This analysis generally required several iterations before a convergent solution was obtained.

INTERNAL LOADS REDISTRIBUTION

Redundancy in the 28/29 wing with the multiple spar construction has some very distinct advantages for fail safe capability, but this same asset makes the structure somewhat more difficult to analyze. Nastran finite element analysis has made this task more manageable and has permitted a better understanding of this complex structure. As the first series of iterations on the inboard spar cap areas were approaching a convergent solution, there was observed a significant redistribution of internal loads from the previous configuration. As material was added to the critical sections, there appeared to be a significant redistribution of internal loads from the less critical areas into the more critical areas (See Fig. 4). Although stress levels decreased in the critical areas, these levels did not decrease linearly with the increase in spar cap area, and the stress levels in the non-critical regions also decreased at the same time. This reduction in stress level in the non-critical areas may have seemed to indicate that material could have been removed from these areas to help reduce weight, but there was obviously another factor to consider. Further area reductions in the non-critical regions would have increased the stresses in the critical regions further, and created a need for more material additions in those regions. This redistribution of internal loads into a few key structural members also raised serious questions as to whether an effective and efficient fail safe qualification could be used for a structure defined in this manner.

As a result of the concern for maintaining an effective and efficient fail safe capability for the 28/29 configuration, a different approach was selected for establishment of the spar cap section properties. This new approach emphasized maintaining an internal load and stress level balance across the chord section of the wing. This was accomplished by initially assigning equal areas to each of the spar caps from the leading edge to the trailing edge, and increasing each spar cap area by an equal increment for each iteration until a satisfactory margin of safety was achieved for the critical member. This worked out quite well and the weight penalties were not quite as severe as was seen in the first approach (See Fig. 5). After acceptable margins of safety were achieved in the critical spars, area reductions were then made on some of the less critical spars. These spars were generally located near the leading edge of the wing and the trailing edge of the wing. These spars were not generally highly loaded, and the reduction in these spar cap areas had little impact on the other spars. Further weight reductions were made by tapering the spar caps in the spanwise direction.

A new material was also chosen for the spar caps inboard of the landing gear rib in order to obtain higher allowables that were more compatible with the wing skin allowables and to also help reduce the weight of these members.

This material was 7075-T73 extrusion, and in addition to the improved allowable values this material also had improved stress corrosion resistant properties over some of the other 7000 series aluminum alloys.

Improvement of the upper surface capability outboard of the landing gear rib was another area which received considerable attention. On previous Learjets the spar caps in this region had been constructed from bent up sheet metal channels which tapered in thickness from the inboard end to the outboard end as opposed to the extruded caps attached to shear webs in the inboard section. All of the spar caps in the wing section outboard of W.S. 53 were of nearly equal areas; thus maintaining a fairly even internal loads distribution. The margins of safety for these members were generally not as deficient as the inboard spar caps, and other methods were used to correct the low margins than were used in the inboard region.

The buckling analysis that was mentioned earlier revealed that there were a number of panels that indicated advanced stages of buckling. To help relieve the spar cap stresses existing stringers that were used on the 35/36 wing were extended further into the outboard sections, and stringers were added to some bays where no stringers had existed previously. This not only caused the skins to carry more load in compression, but also added more basic area very near the outside fiber to help reduce the bending stresses on the spar caps. In some areas the use of wing skin stringers was not sufficient to obtain satisfactory stress levels and local reinforcements were added.

PRELIMINARY WEIGHT ESTIMATES

Preliminary weight estimates were arrived at with the aid of the weight calculation routine in Nastran. Two PARAM cards were inserted into the Bulk Data deck. The first PARAM card called out the GRDPNT option, and the second card called out the WTMASS feature. Accordingly, density factors were added to all of the material cards. A model 35/36 wing was run first to determine a base line weight upon which weight increases for the 28/29 wing would be determined. Although this routine does not include such detail factors as fuel sealer weights, control mechanism weights, and other miscellaneous factors, the preliminary weight estimates were still considered to be a reasonably accurate measure of weight increase over the 35/36 wing.

DOWN BENDING ANALYTICAL QUALIFICATION

Originally both the up bending and down bending ultimate load conditions were proposed to be qualified by analysis. Although there was a great deal of analytical work done on the up bending load condition, this load case was eventually qualified by static test due to the tight schedule and lack of man power availability that was prevalent at that time. However, the ultimate down bending load case was certified by analysis. The down bending load condition was not as critical as the up bending load condition, and the 28/29 wing did not require nearly as much rework for this condition as was necessary for the up bending condition. A comparison of the 28/29 down bending loads with the 35/36 down bending loads showed that the 28/29 loads were greater than the 35/36 loads, but not by a large amount. Considering the material additions to the lower wing skin thickness, there was very good reason to expect that the stress levels might be very nearly the same.

To achieve this analytical qualification a correlation was first established between the 35/36 wing static test strain levels and the 35/36 Nastran strain levels inboard of W.S. 181.10. A comparison was then made between the 35/36 Nastran strain and the 28/29 Nastran strain levels. Im almost every location the 28/29 wing Nastran strain levels were less than or equal to the 35/36 Nastran strain levels. In those areas where the 28/29 wing down bending strains exceeded the 35/36 down bending strains margins of safety were calculated, and in all cases these margins of safety were shown to be more than adequate.

The wing structure between W.S. 181.10 and 244.10 commonly referred to as the six foot extension was qualified by analysis and proof load tests. Generally the stress levels in this section were low and had quite high margins of safety. The structure outboard of W.S. 244.10 consisted entirely of the winglet and winglet attachment structure. Due to the complexity of this member, certification was accomplished with a static test for both the up bending and down bending conditions. Typical plots showing the relationship between the 35/36 wing experimental data, the 35/36 Nastran wing data, and the 28/29 Nastran wing data have been shown in Figures 6 thru 9.

STATIC TEST UP BENDING CORRELATION

There were over 400 strain gages installed on the 28/29 wing static test article. This was more than twice the number of gages installed on any previous Learjet wing test. All the strain gages were installed on the right hand wing to simplify the installation and instrumentation. During the static test these gages were monitored on a cathode ray tube (CRT) using an interactive graphics program. This program provided a quick means of monitoring the status of the static test article and identifying areas that could become critical. Upon command the program would list the top 15 gages in tension and compression on the CRT as well as on a hard copy printer. Warnings were also issued for non-linear gages above a certain strain level, and individual stress versus load plots could be obtained within seconds for any strain gage channel. Using previously calculated Nastran stresses in key areas, a comparison was made with the appropriate strain gage channel to determine whether the test was proceeding as planned. This approach proved extremely valuable in monitoring and controlling the static test (See Fig. 10).

At the conclusion of the static test the strain gage results were used for a more detailed comparison with Nastran analytical results. The correlation of this experimental data with the Nastran data was generally very good for the majority of strain gage locations. Agreement was probably best in the wing section outboard of the landing gear rib where the structure was most uniform. Correlation in the section inboard of the landing gear rib was good, but in some locations there was more noticeable deviation which appeared to be significantly influenced by structural cutouts and discontinuities in the vicinity of the gage attachment. Figure 11 shows the strain values on the spar 5 upper cap, and Figure 12 shows the strain values on the spar 5 lower cap. These values correlate quite well except in the area of the carry through fittings at wing station 53. These fittings were installed to maintain continuity of the spar caps which were interupted by the landing gear rib at this point.

Correlation of the strain gage values and the Nastran results were shown in Figure 13 for the spar 4 upper cap and in Figure 14 for the spar 4 lower cap. Again agreement was generally very good except in a couple of areas. The first area was mentioned previously in regard to spar 5 in the vicinity of the landing gear rib. The other area of some deviation was in the area adjacent to the W.S. 181.10 rib. Here the wing skins were discontinuous and were spliced by a fingered and contoured splice plate both upper and lower. The spars were also discontinuous in this region, and splices were installed for spar cap continuity.

RESULTS AND CONCLUSIONS

The Model 28/29 wing development at Learjet was significantly influenced by Nastran analysis. Configuration development and member sizing were performed much more accurately and faster than could have been done previously. This permitted Learjet to determine the impact of changes in the wing structural arrangement and member section properties on stress levels, internal loads, and aircraft weight at a much earlier point in the wing development.

Substantiation of the 28/29 wing was accomplished by a combination of testing and analysis where Nastran was the basis for much of the analytical work. During the static test phase of certification there were no structural failures in the 28/29 wing due to any of the design load conditions. Correlation of the analytical results with the experimental data was generally very good except in areas where there were discontinuities. The ultimate down bending load condition was qualified by Nastran analysis which reduced the cost and lead time for this segment of the certification.

REFERENCES

1. Abla, Mike H., Boroughs, Robert R. and Cook, Everett L. Analysis of The Learjet 35/36 Wing and Correlation with Experimental Results, pp. 331-352, Nastran User's Experiences, TMX-3428, October, 1976.

2. The Nastran User's Manual (Level 17.0), NASA SP-222(04), Washington, D.C., December, 1977.

3. Bruhn, E. F.: Analysis and Design of Flight Vehicle Structures. Tri State Offset, 1973 (pp. A19.1).

FIGURE 1 - LEARJET MODEL 35/36 AIRCRAFT

FIGURE 2 - LEARJET MODEL 28/29 AIRCRAFT

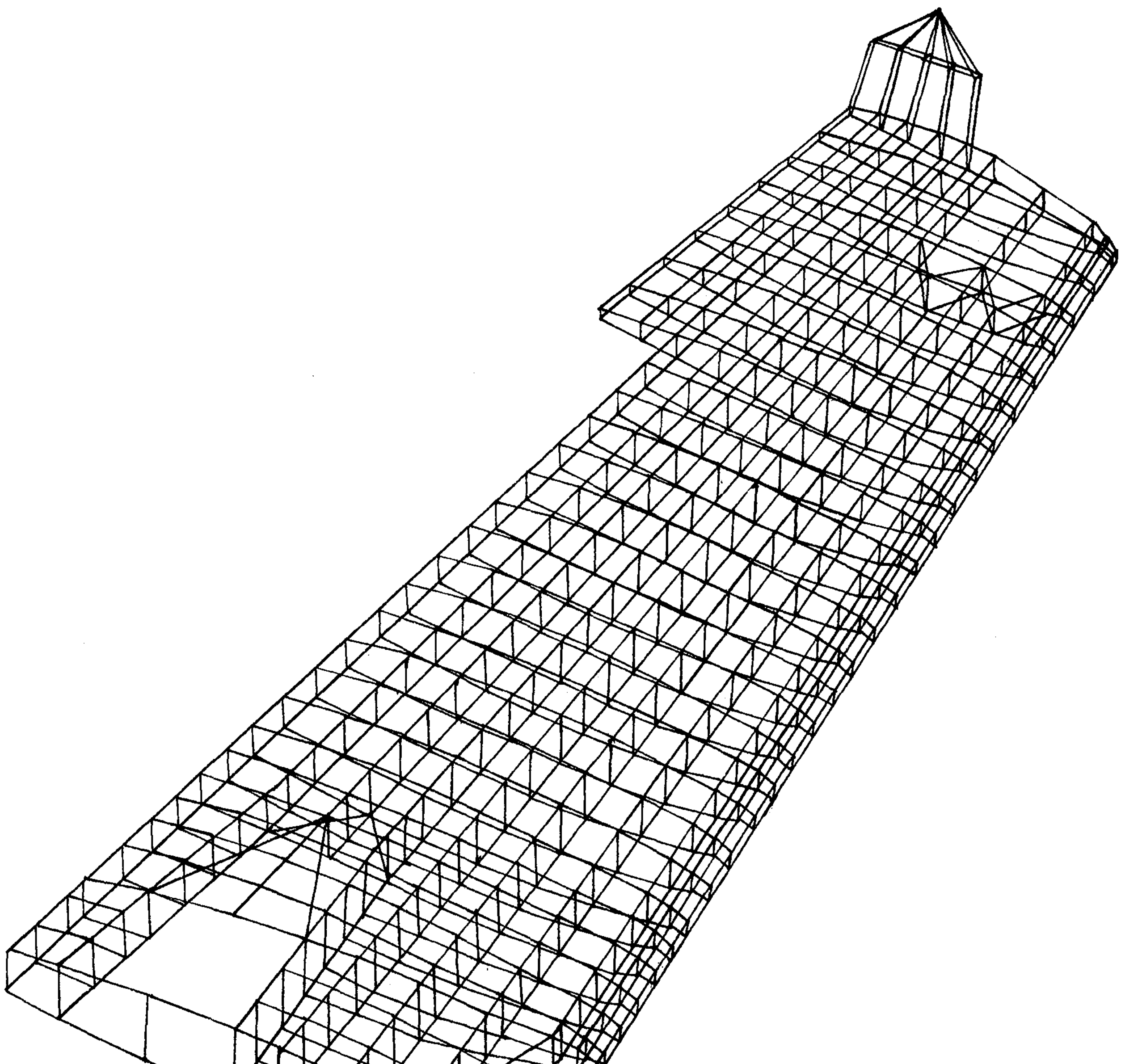

FIGURE 3 - NASTRAN 28/29 WING MODEL

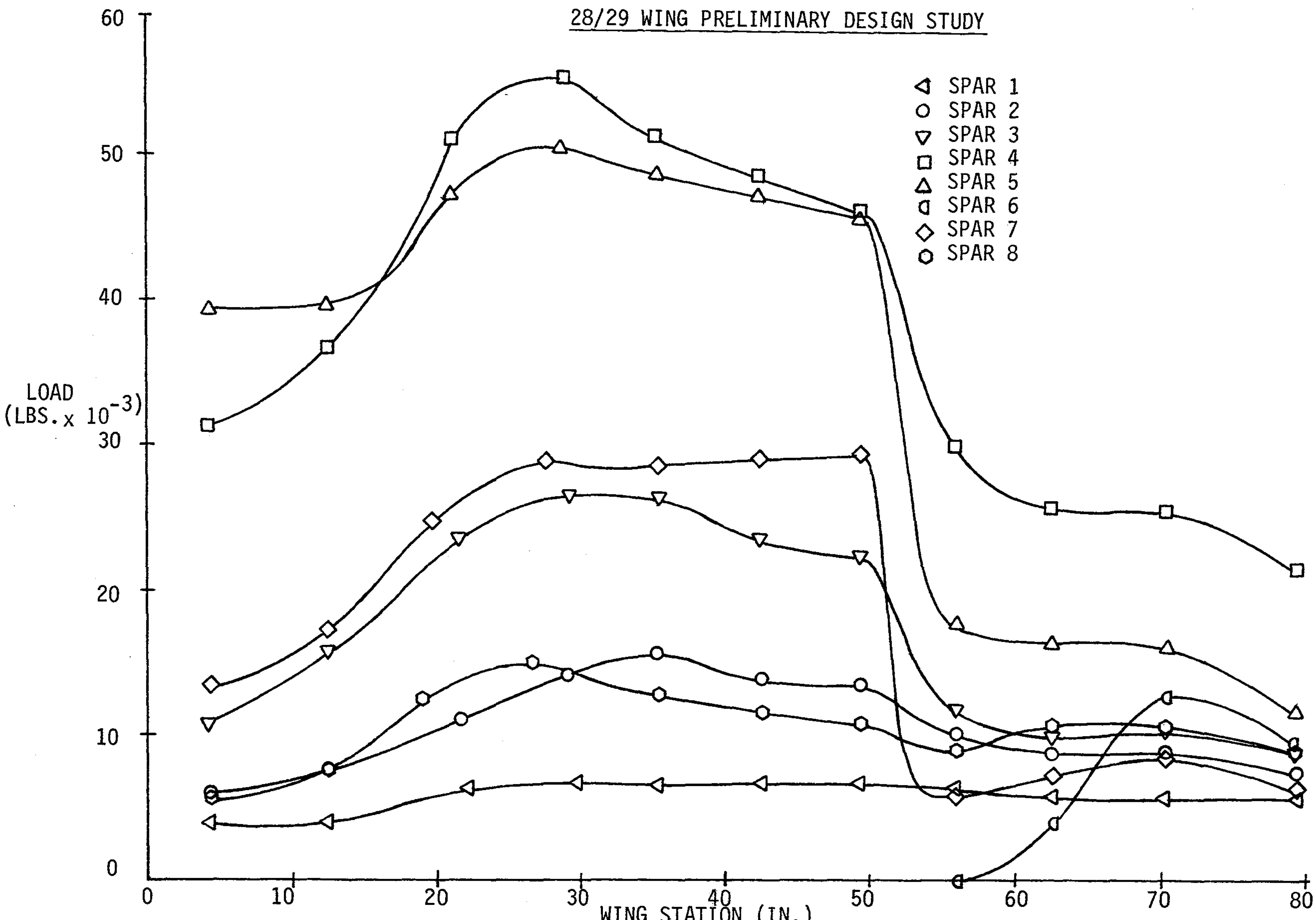

FIGURE 4 - SPAR CAP INTERNAL LOADS (UNEQUAL AREAS)

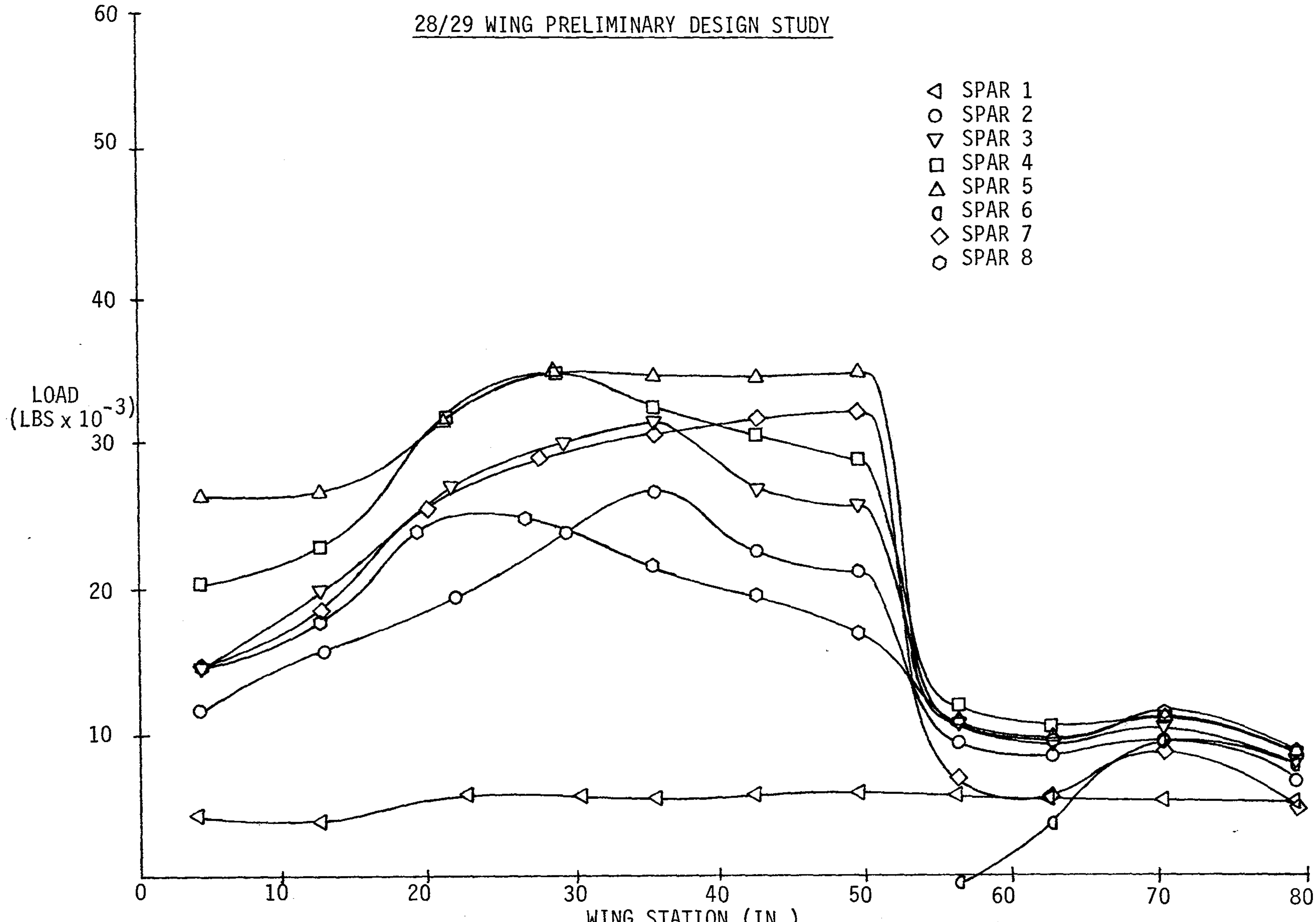

FIGURE 5 - SPAR CAP INTERNAL LOADS (EQUAL AREAS)

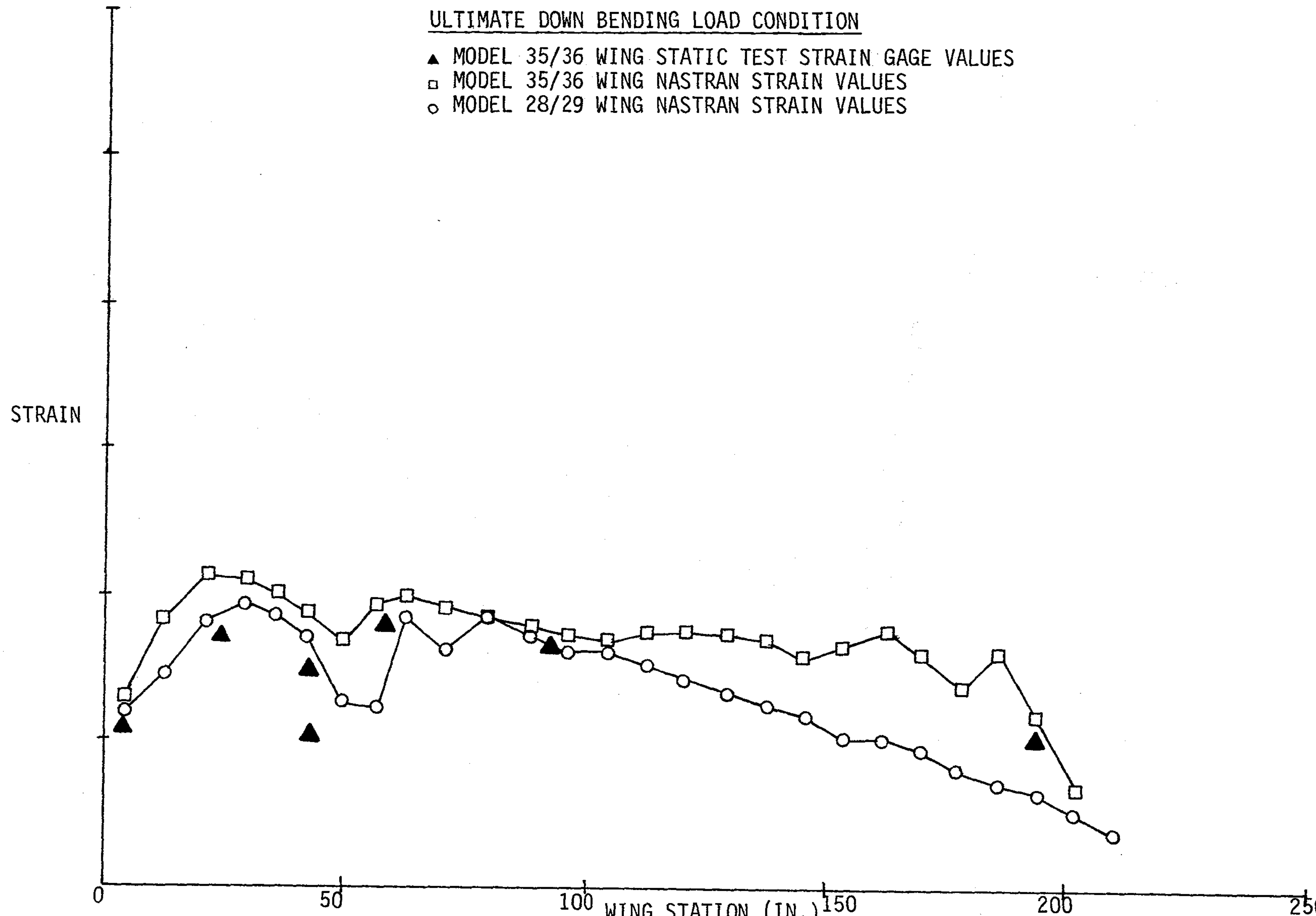

FIGURE 6 - STRAINS IN UPPER SPAR CAP 4 (DOWN BENDING LOADS)

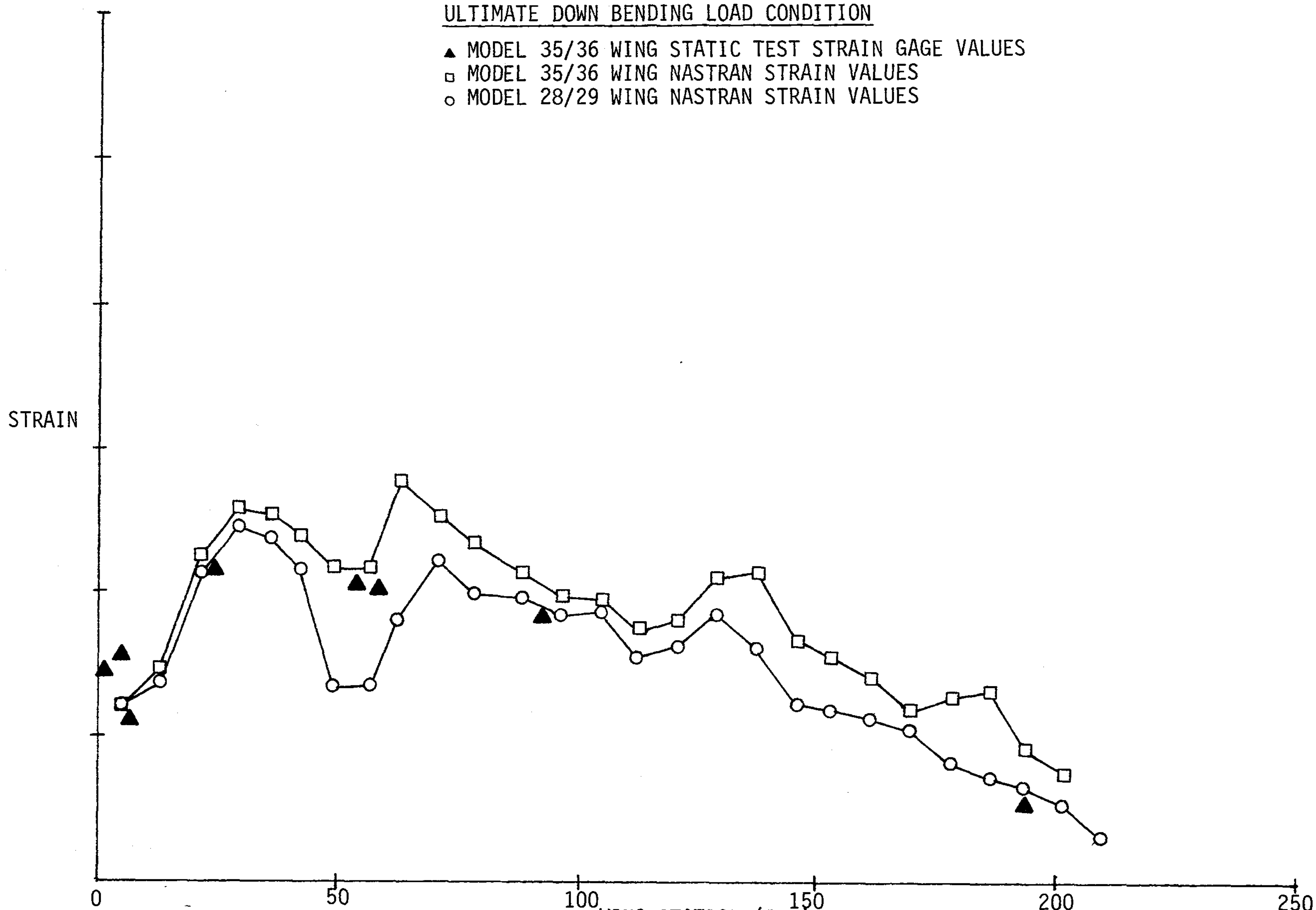

FIGURE 7 - STRAINS IN LOWER SPAR CAP 4 (DOWN BENDING LOADS)

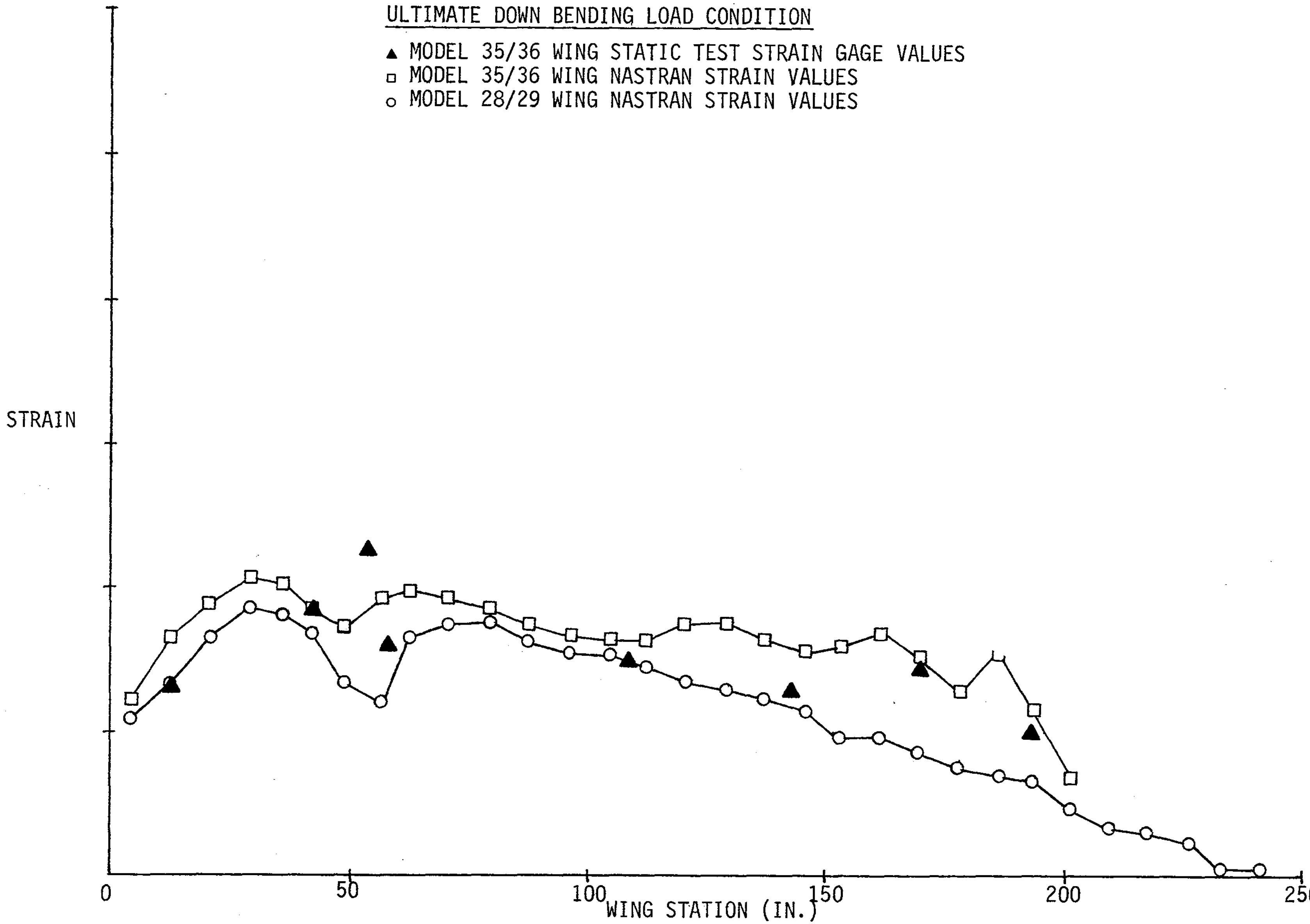

FIGURE 8 - STRAINS IN UPPER WING SKIN BETWEEN SPARS 3 & 4

(DOWN BENDING LOADS)

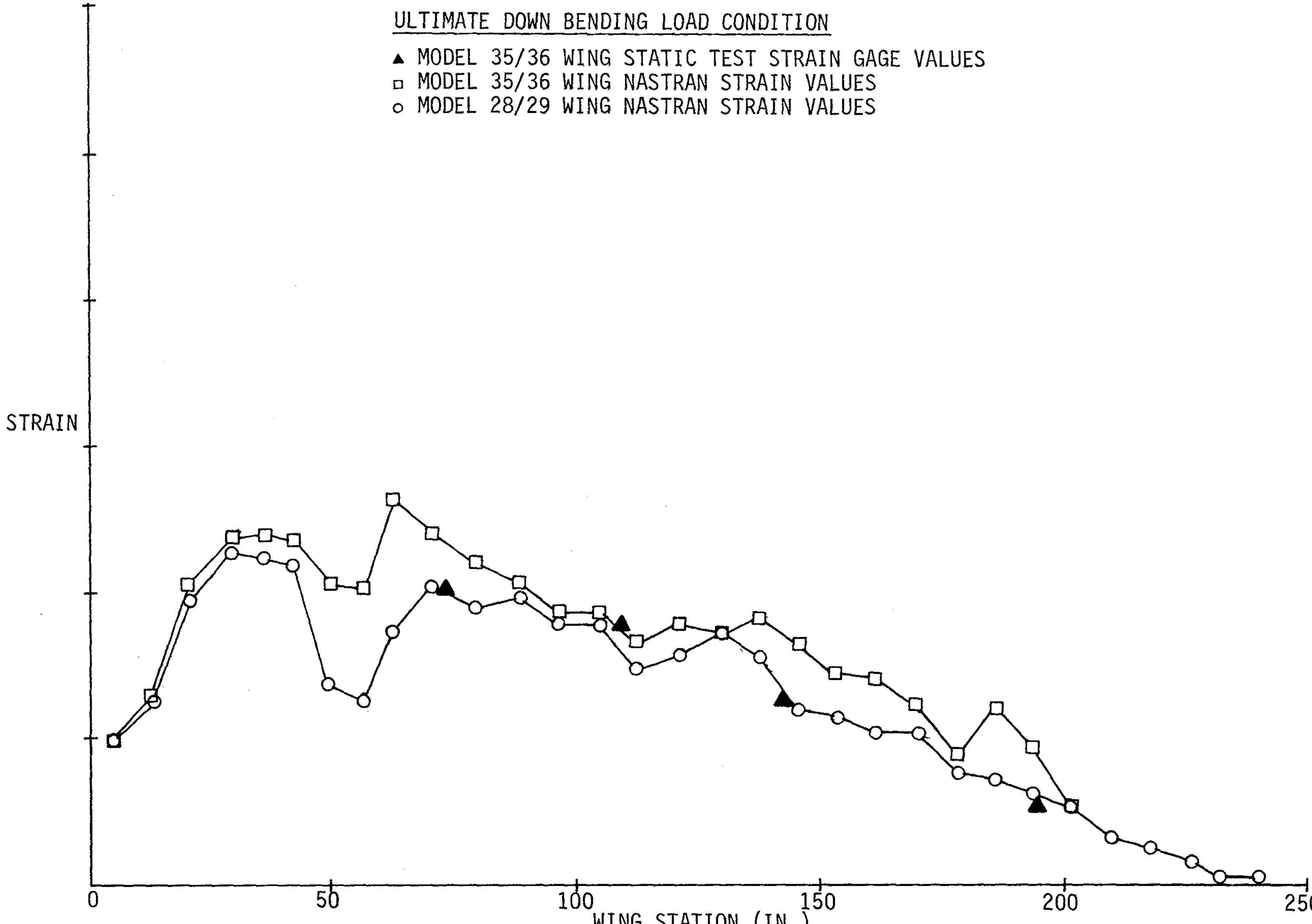

FIGURE 9 - STRAINS IN LOWER WING SKIN BETWEEN SPARS 3 & 4

(DOWN BENDING LOADS)

FIGURE 10 - MODEL 28/29 WING STATIC TEST SET-UP

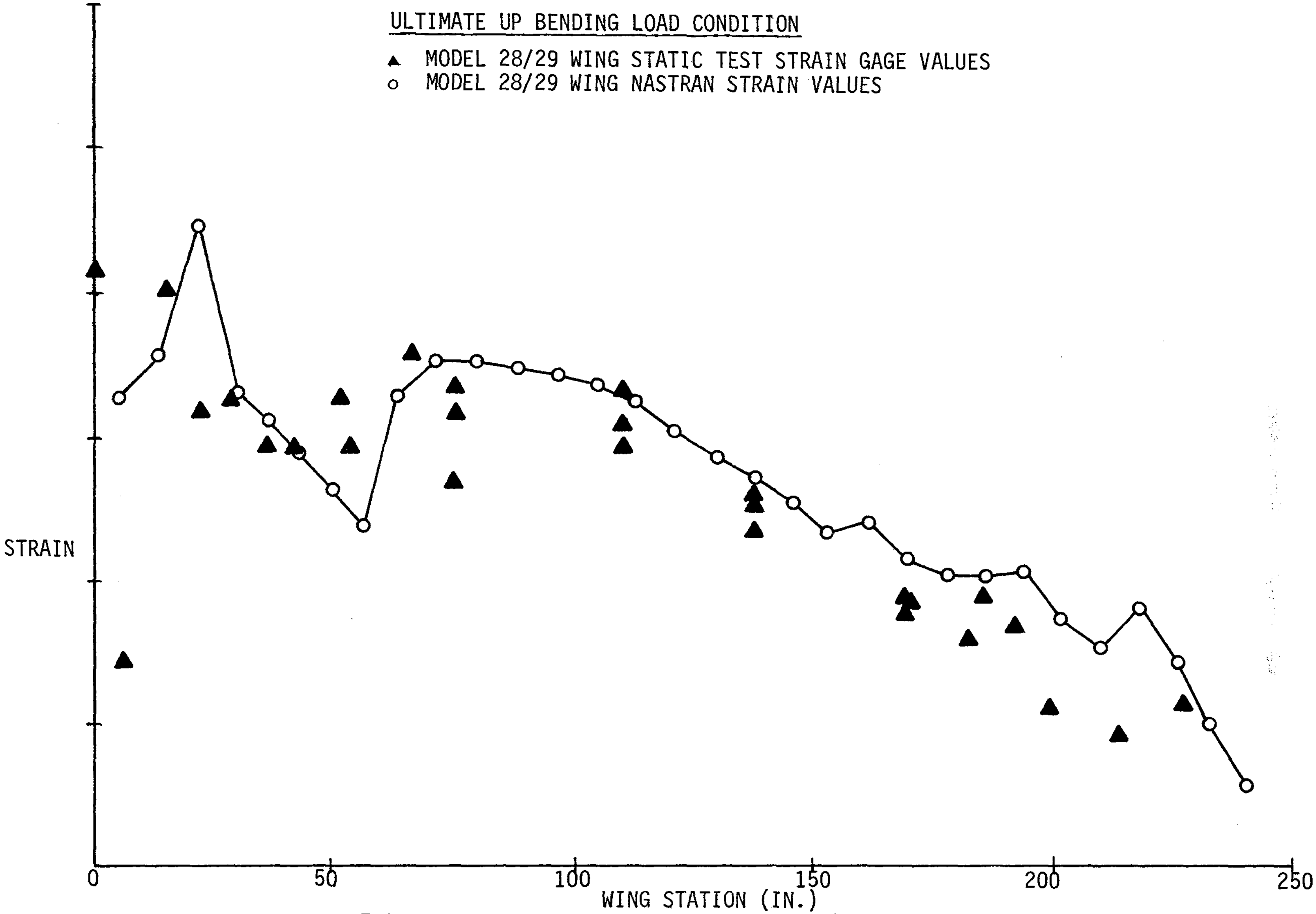

FIGURE 11 - STRAIN IN UPPER SPAR CAP 5 (UP BENDING LOADS)

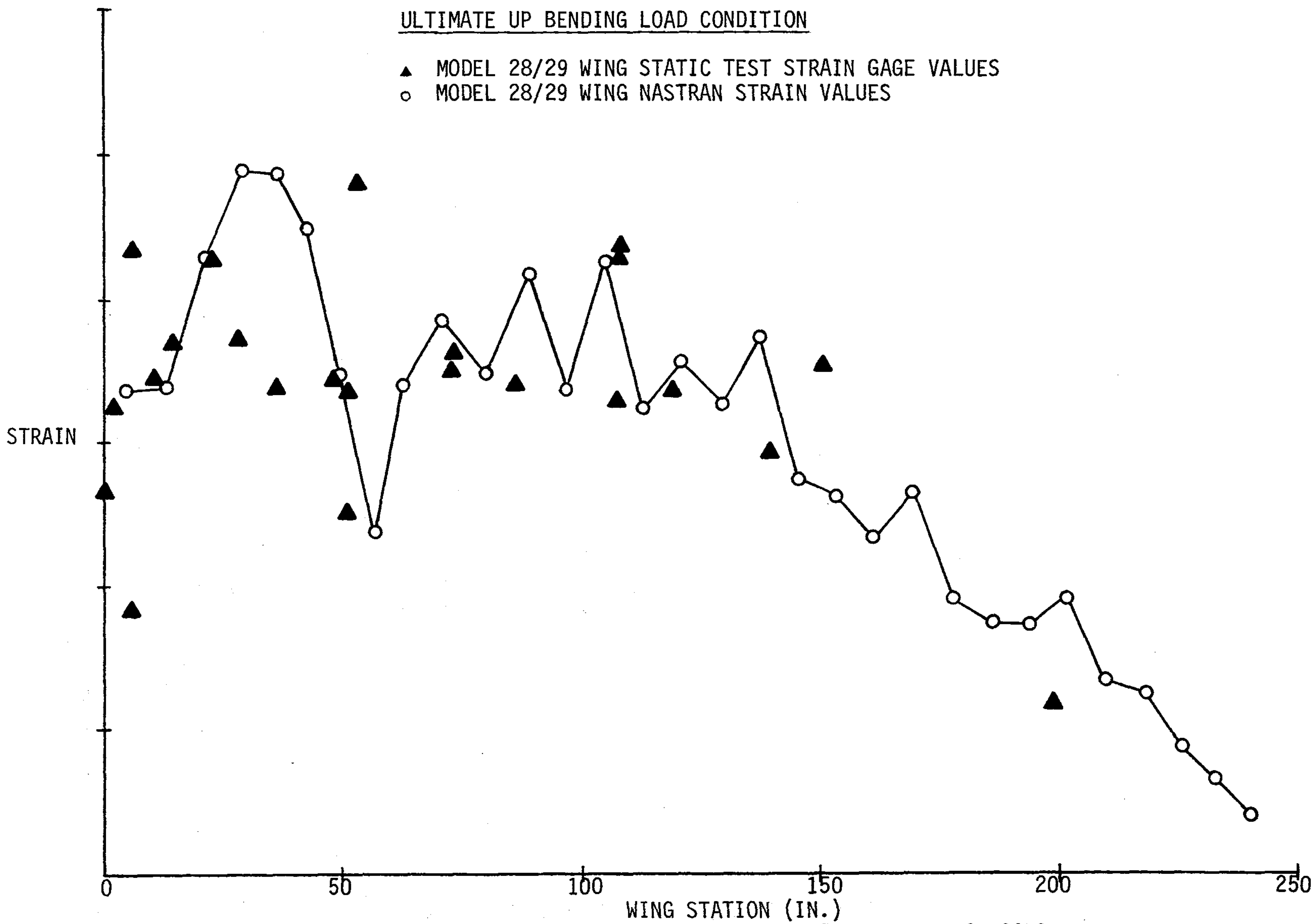

FIGURE 12 - STRAIN IN LOWER SPAR CAP 5 CUP BENDING LOADS

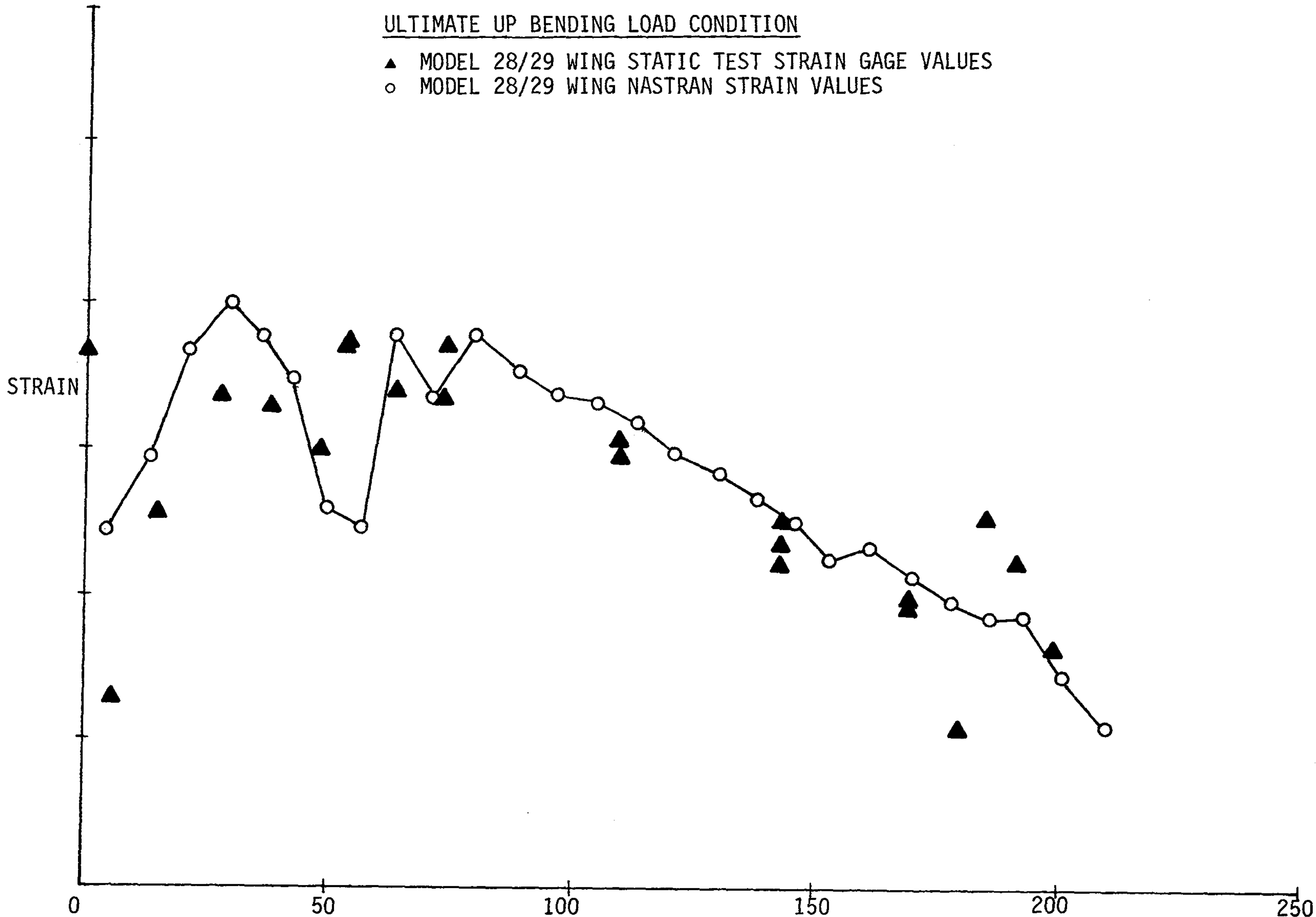

FIGURE 13 - STRAIN IN UPPER SPAR CAP 4 (UP BENDING LOADS)

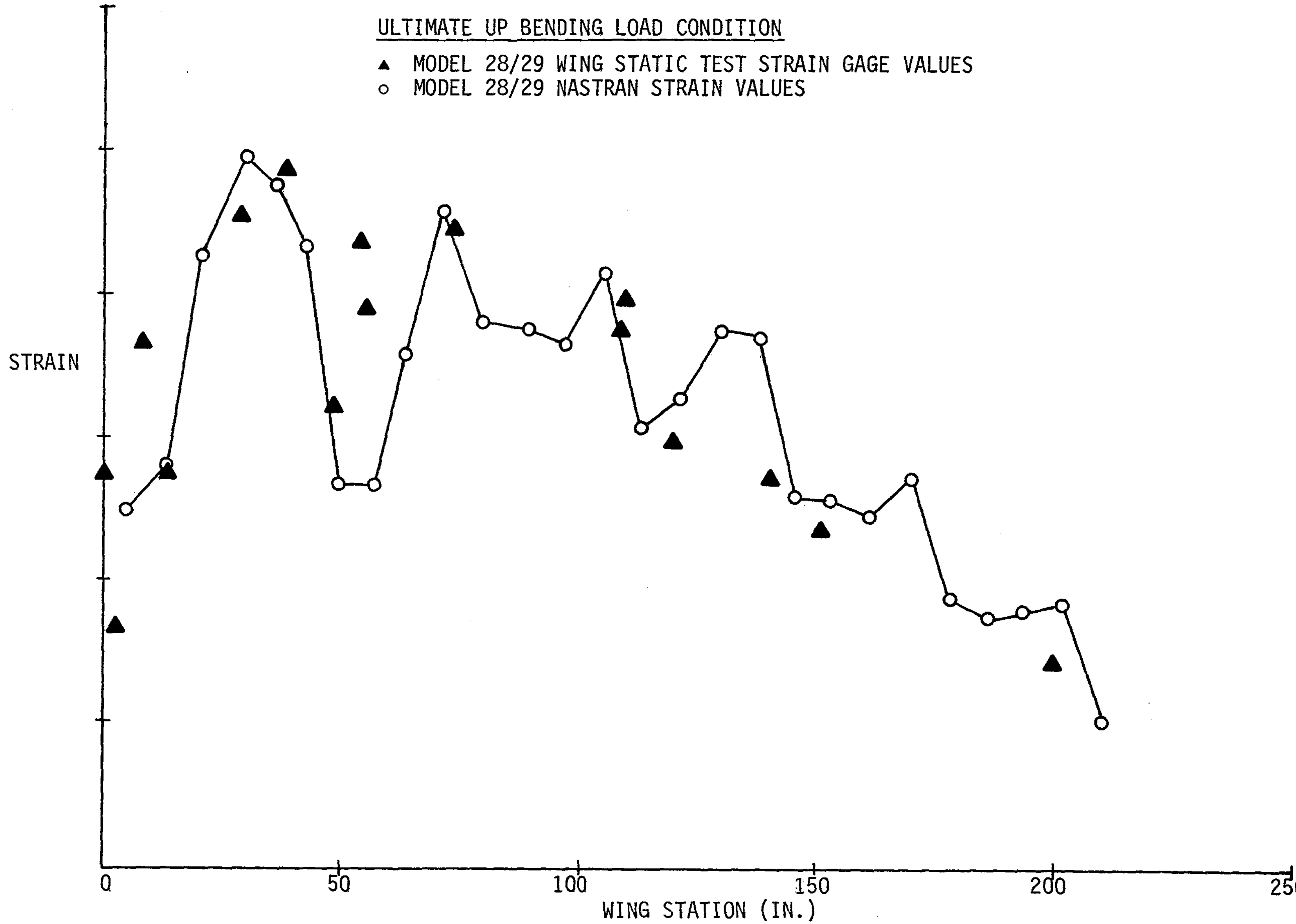

FIGURE 14 - STRAIN IN LOWER SPAR CAP 4 (UP BENDING LOADS)