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TECHNICAL MEMORANDUM

title: COMPARISONS BETWEEN SMALL-SCALE CABLE DYNAMICS EXPERIMENTAL RESULTS AND SIMULATIONS USING SEADYN AND SNAPLG COMPUTER MODELS

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ABSTRACT

The Civil Engineering Laboratory (CEL) has recognized the need for reliable simulation methods for predicting the motions of underwater cable structures, and is engaged in a major effort to develop the capability for analyzing such structures during deployment, operations, and recovery. To accomplish this goal, work is currently underway on a wide range of studies, ranging from prediction of barge motions to development of new drag measurement techniques.

This report is the first in a series that will deal with evaluations of computer models used by CEL for the analysis of underwater cable structures. In this report results from a finite-element program, SEADYN, and a lumped-mass program, SNAPLG, are compared to experimental data from a series of tests conducted with 6-ft long cables.

A total of 17 comparisons were made, including: single point mooring relaxations, simulated anchor-last deployments, bi-mooring relaxations, and single and dual cable suspended loads with forced oscillations of the cable. Graphical comparisons are included showing: nodal positions of the cable, velocity of the anchor/buoy, and tensions at the fixed end of the cable.

These comparisons have shown that both SEADYN and SNAPLG are useful tools for simulating the dynamic behavior of ocean cable structures. Both models, however, had difficulty simulating a stiff cable and slack conditions.

INTRODUCTION AND BACKGROUND

With increasing frequency, large and complex cable-based structures are being implanted in the ocean. To insure success during all phases of a structure's life, designers must be able to predict its behavior in response to transient and steady-state excitations. This includes: the implant, when the structure is subjected to transient loadings; operational life, when allowable structural deformation may be restricted to precise limits during given environmental conditions; and extreme environmental conditions, when the structure must survive intact to resume its intended function when conditions return to normal.

Under the sponsorship of the Naval Facilities Engineering Command, the Civil Engineering Laboratory (CEL) has been developing and evaluating methods to analyze cable structures in the ocean. Both lumped parameter and finite element models are used to simulate static and dynamic deformations of the structures. The models are general so that a variety of problems can be solved using several different solution algorithms.

Before the models can be used with confidence, they must be validated by comparison to experimental data. Should there by significant differences between model predictions and experimental data, particular portions of the models will be identified for modification and revision. Comparisons using a wide variety of experimental configurations to test the capabilities of the models can define how closely the models predict real events and thereby establish their validity.

A series of experiments was devised to test various aspects of the models. The experiments ranged in size from laboratory to prototype scale. While some of the experiments were small in size, they were not considered scaled models but as full-size events of their own. The philosophy behind this approach was that the computer models are inherently capable of analyzing any structure, regardless of size. Therefore, a close comparison between a small-size, easily set-up, inexpensive experiment and a prediction would serve to validate the model. Scaled models were not used in the experiments because, generally, it is not possible to satisfy all the appropriate scaling laws simultaneously. Thus, the results from a scaled model experiment could not be used successfully to compare with a computer model of the full-size structure. However, the computer model is capable of simulating the response of the small-size model itself because no scaling is involved. As a matter of completeness, and to insure that no unforeseen effects of scale (size) influenced the results, tests were conducted in sizes that used cables ranging from 6-ft to 60-ft to at-sea operational lengths (3000 ft).

This report is one of a series of reports describing the comparisons between experimental results and computer model predictions. Data from the 6-ft long cable experiments are presented in Reference 4, from which several example cases were selected for this comparison. Calculations from both models are shown so that differences in the modelling techniques and/or the models themselves can be seen.

SIMULATION MODEL ABSTRACTS

The two models evaluated in this comparison are named SEADYN and SNAPLG (Ref 2,3). SEADYN utilizes finite element techniques while SNAPLG is a lumped parameter model. Both models calculate both static and dynamic responses of cable structures. SEADYN is somewhat more general in its formulation so that it can handle a greater variety of problems; however, problems are sometimes easier to formulate for SNAPLG.

SEADYN

SEADYN (Ref 2) is capable of performing non-linear analyses of both branch and series connected submerged cable structures. Static, dynamic, nodal, and frequency domain analyses can be performed for complex systems which include buoys, anchors, fixed points, different cable materials, and payout or reel-in. An option exists to analyze mooring systems for surface ships. Loadings may result from point loads, non-steady three-dimensional current fields, surface waves (or spectra) and wind loadings.

Non-linearities arising from large displacements, large strains, velocity-squared drag, and position-dependent loadings, hyperelastic materials and constraints on the surface and bottom of the current field are all treated. Bending and twisting effects are not modelled.

Though the program is considered to be a finite element model, lumped parameter techniques are also used. A variety of incremental solution techniques are available including linearized, self-correcting, and iterative. Three basic types of analyses can be performed:

DEAD: Static shape with gravity loads only

LIVE: Static shape with current, wave, and point loads

DYNAMIC: Transient response of a system starting at equilibrium

Additional options include calculating natural frequencies and mode shapes; checking the adequacy of anchors (holding capacity), buoys (buoyancy), and lines (strength), and calculating strumming drag coefficients. The modelling techniques, solution options, and analysis types combine to allow a high degree of versatility in achieving the desired accuracy in a solution at minimal cost.

SNAPLG

SNAPLG (Ref 3) simulates non-linear static and dynamic responses of two-dimensional, series-connected cable structures. The program can model dynamic tensions, including snap loads, during transient conditions and/or payout/reel-in operations. Loadings can be from surface waves, steady ship velocity, or a non-uniform current profile. A lumped spring-mass model is used and solved by a finite difference technqiue. Because the model is less general than SEADYN problems are more easily set-up and execution times are usually shorter.

Applicability of the Models

Experience with both SEADYN and SNAPLG has shown that both models are useful in calculating the static and dynamic behavior of ocean cable structures. However, experience has also shown that in some applications the results from both models can become unreliable.

The most difficult situation for both models to simulate involves slack cable elements. Major approximations to dynamic cable behavior are required when a zero-tension element is calculated in either model, which occurs when the calculated element length is equal to or less than the unstretched length.

SEADYN approximates the behavior of the slack element by either allowing it to support a compressive load, or by removing it from the system (except for the drag loading) and allowing the two end points of the connecting elements to move independently. In the latter method the slack element is re-introduced when the distance between the two end nodes exceeds the unstretched length, but this new configuration of the system is not in equilibrium. The combination of the independent end point behavior and subsequent equilibrium calculations results in errors which can remain in the system for long periods of time.

SNAPLG handles slack elements in a slightly different manner. When element strains drop below a prescribed limit (0.0001), the effective spring constant (i.e., rigidity) of the element is reduced by a value proportional to that strain, even during compression. In this case the element is removed only after its calculated length drops to zero. The variable spring constant reduces but does not eliminate the discontinuities in system behavior which result from the removal and re-addition of slack elements.

A second sensitivity of both models involves the cable rigidity and time step. As rigidity increases, the sensitivity of the tension calculations increases because of the large tension changes that result from small changes in segment length. This can be remedied in some situations by decreasing the small time step and displacement error bounds.

A final limitation involves internal damping in the cable material, which is neglected in both models. Lack of internal damping could cause significant differences between the measured and simulated cable behavior, especially if the material shows significant hysteresis.

OVERVIEW OF EXPERIMENTS AND RESULTS

The objective of all the cable experiments in this series was to provide high quality experimental data over a wide range of cable geometries and loadings, for use as a standard by which SEADYN and SNAPLG could be evaluated. This objective was fully satisfied in the 67 tests resulting from the 6-ft cable experiment (Ref 1). Five types of tests were made:

(1) Simulated anchor-last deployments, wherein one end of the cable is fixed at the surface and the other end, with an anchor attached, is allowed to fall freely.

(2) Single point mooring relaxation experiments in which a buoy anchored to the bottom by a single cable is displaced from equilibrium and allowed to return.

(3) Bi-moor relaxation in which two cables are attached to a common point on a buoy and the free ends are fixed to the bottom at separate points. The buoy is displaced in or out of the vertical plane with the bottom fixed positions and allowed to return to equilibrium.

(4) Single cable suspended load, in which an anchor is suspended from a single cable attached to a vertical oscillating point.

(5) Dual cable suspended load in which two cables are attached to opposite sides of an anchor or buoy and the free ends are attached, one to the bottom and one to an oscillating point near the surface.

These test configurations are shown in Figure 1.

The experimental data for the single point mooring relaxations and simulated anchor-last deployments consist of nodal positions of the cable versus time (reduced from photographic data), and tensions at the fixed end of the cable. Velocities and accelerations of the free end (buoy or anchor) are also presented. For the remaining 3 types of tests only tension histories were recorded.

The experimental results are presented in tabular and graphical forms and are contained in a separate set of reports (Ref 4).

The error bounds on the directly measured experimental data were all found to be within acceptable levels (Ref 1). General error bounds on the reduced and derived data are given by:

(1) Displacement - Accurate to within 1/2 in. in the X, Y, and Z directions.

(2) Velocity - The velocities used for these comparisons are total velocities, numerically derived from the displacements. The total velocity error is therefore due to the error inherent in the differencing technique. The magnitude of the error is unknown.

(3) Acceleration - The accelerations were derived from the velocities, and are considered to be estimates only. No acceleration comparisons were made.

(4) Tension - The tension data were obtained by sampling every 10 msec and averaging over each 0.1 sec. These values are considered to be sufficiently accurate for these comparisons; the linearity of the tensiometer response was within 0.05% full scale.

(5) Time - Many of the tests required a time shift for $t = 0$. The actual zero time was determined by visually analyzing the photographic data, and is only as accurate as the frame rate (± 0.1 sec). Small shifts in time between the experimental and computer calculations are assumed attributable to this error.

OVERVIEW OF COMPARISONS

A total of 17 tests were selected from the 67 tests for comparison to the computer models. These tests were selected as representative of the full range of experimental conditions within each of the five types of tests. In some cases, tests were chosen because test results exhibited a distinctive behavior or phenomenon not found in the other tests.

Properties of the anchor, buoy, and cables are included in Table 1; major parameters for each experiment used in this report are included in Table 2 along with a listing of the comparisons. Readers are referred to Reference 1 for further information regarding the experiments.

Comparisons are presented on a test by test basis arranged in numerical order by type. The performance of both models is discussed relative to the experimental parameters for each test, and summarized for each type. For the graphical comparisons the calculations from both models are plotted along with the experimental results.

COMPUTER MODELLING

Inputs to both SEADYN and SNAPLG fall into three separate categories. The first category includes the physical parameters of the cable system such as cable properties, lumped body sizes (anchors and buoys), and appropriate environmental and loading conditions such as the magnitude and direction of a current or surface waves, or constraints on specified cable locations due to attachment to a ship. Inputs in this category are usually constants, and do not require any interpretation by the programmer.

The second category of inputs to these models does require efforts by the programmer because it involves the transformation of the true system to a discrete mathematical approximation. This transformation usually requires a compromise between accuracy in the model and cost of the solution, based on the level of discretization used. The cost of getting the desired solution(s) is also dependent on a second group of solution parameters which define the required accuracy of the calculations once the system is modelled. Careful attention must be paid to the selection of these solution parameters (such as error bounds, time steps and damping) to assure that they are compatible with the model; results from a poorly defined model cannot be improved by increasing the accuracy of the calculations.

Even an experienced programmer cannot be expected to produce "the" unique set of solution parameters which best simulate a problem, without first trying several variations. With one problem, a programmer can often fine-tune the accuracy of the results by varying certain parameters. However, this procedure becomes very time consuming and expensive when many problems are to be modelled, as in these comparisons. Instead, a standard set of input parameters was selected as applicable to all the tests so that a relative comparison could be made between the results of the two models. This would still allow for meaningful interpretation of the results with a minimum of effort in each case, and the model results in this report should be interpreted with this philosophy in mind.

The third category of inputs to both SEADYN and SNAPLG includes the variable parameters which describe system behavior, such as drag and added mass coefficients. In modelling real systems, approximations are often required to allow for the treatment of irregularly-shaped bodies as cylinders and spheres. In these instances, typical input parameters for defining the drag force would include "equivalent diameter" as well as drag coefficients versus Reynolds Number. Since regularly-shaped bodies (cylindrical cables and spherical buoys and anchors) were used in these experiments, only the values of the drag coefficients were needed to define the fluid drag loads. But because of the many factors affecting cable drag (e.g., surface roughness, cross-sectional shape, strumming), it is difficult to accurately predict the actual drag coefficients for ocean cables. The only reliable way of determining these coefficients is to conduct a drag measurement experiment for each application. When such measurements are not available, the "default" drag coefficients in each program can be used. These default coefficients are approximate values intended to give reasonable results for most applications, and they were used in these comparisons.

In SEADYN the default drag coefficients are dependent on Reynolds Number as shown in Table 3. In SNAPLG, constant drag coefficients are used, rather than Reynolds Number dependent values. For the cylindrical cables, the normal drag coefficient was 1.35 and the tangential drag coefficient was 0.025. Both values are normally used for SNAPLG, so they were not adjusted for these comparisons. The drag coefficient used for the spherical lumped bodies was 0.50.

In both SEADYN and SNAPLG, cables are approximated as a series of short, straight-line segments, with the loadings for each segment assumed constant. The accuracy of the approximation to a continuous curved cable is therefore dependent on the number of segments, especially in regions of high curvature such as the free end of a cable during an anchor-last deployment. For each test, segments were defined identically in each program to allow for a fair evaluation of each model. For most tests these segments corresponded to the locations of the segments on the experimental cable.

SINGLE POINT MOORING RELAXATION COMPARISONS

Test 6

As shown by the displacement comparison in Figure 2, both models worked well for this set of experimental conditions. In Figures 3 and 4 buoy velocity and cable tension comparisons are shown only for SEADYN; the results from SNAPLG for this and the remaining buoy relaxations were identical in behavior to both SEADYN and the experiment, so they were omitted.

The velocity comparison shown in Figure 3 shows characteristics typical of both the experimental and predicted velocities throughout the single point mooring relaxation tests. In this and most of the remaining velocity comparisons, the SEADYN calculations are higher in magnitude and much smoother in time than the experimental values. This difference is considered to be related to the drag coefficients.

The tension comparison in Figure 4 shows that SEADYN modelled the cable tension accurately in both magnitude and behavior. The agreement between the tensions during the initial transient stage is significant, as the largest tensions often occur at this stage. For the steady-state tensions agreement is also good; the experimental tensions appear smoother than they actually were because of the round-off error used in the data reduction.

Test 7

SNAPLG was not compared to Test 7 because of its similarities to Tests 8 and 9. Figure 5, therefore, shows only a SEADYN displacement comparison. Figure 5 also shows several characteristics common to many of the displacement comparisons of this type. First, the accuracy of the experimental results is evident by studying the initial position of the cable. Many tests exhibited the same unnatural hump next to the fixed end, which is assumed to be due to the technique used in reducing the photographic data. A smaller number of tests also showed an unexplained cable shape near the free-end; the slightly convex curve indicated by the last few nodes should not occur with the negatively buoyant cables. Since all tests were started from a dead rest this phenomenon seems again attributable to the error in the reduction process. Figure 5 also shows the predicted nodal positions from SEADYN leading the experimental nodal positions. This difference is assumed to be attributable to the magnitude of the default drag coefficients used.

Experimental and SEADYN calculated velocities for the buoy motion are shown in Figure 6. These are resultant velocities for the two directions of motion. SEADYN velocities are slightly higher as expected from the displacement comparison.

The tension comparison is shown in Figure 7. The SEADYN magnitudes compare well with the experimental tensions, but the model failed to predict the initial "spikes" measured in the experiment.

Test 8

The nodal positions calculated by SEADYN and SNAPLG for Test 8 are close to the measured positions, as plotted in Figure 8. The velocity comparison in Figure 9 shows good agreement for both models. The tension comparison in Figure 10 shows an error in the zero-time shift of the experimental data because of the 0.1 second delay in the initial rise. This time shift in some tests was a result of the data reduction process. Even considering this, both models show a significant difference compared to the experimental results since they miss the initial snapload and steep initial rise.

Test 9

This test was the most difficult of the three for the models to simulate because it involved the stiffest cable material (nylon). As shown in Figure 11 SNAPLG modelled the nodal positions better than SEADYN; the same is true for the buoy velocities shown in Figure 12. In the tension comparison (Figure 13), SNAPLG again has the closest fit, although neither calculation shows the basic behavior recorded in the test.

Test 19

This test was selected as representative of the taut cable mooring relaxation tests. Figures 14, 15, and 16 show that the model calculations agreed very well with the experimental results. Note that the experimental tensions appear to be 0.1 second ahead of their "expected" positions, presumably due to the time-shift.

Summary of Tests 7, 8, and 9

Tests 7, 8, and 9 were chosen for comparisons because their experimental parameters differed only in the type of cable. This allowed for an analysis of the effects of cable rigidity on the experimental and model results, and for relative comparisons between the two.

Figures 17, 18, and 19 show a comparison of nodal positions, buoy velocities, and fixed-end tensions for the three experiments. These figures are useful in determining the effect of cable rigidity, which differed by a factor of more than 15, in the small-sized experiments. No conclusions regarding rigidity effects can be drawn from the nodal displacement comparison since the nylon cable had a much smaller diameter (0.1 in. versus 0.163 in.) than the other rubber cables. The displacement comparison will be useful, however, for comparison to the relative nodal positions calculated by the models. The velocity comparison, Figure 18, shows that the initial spike and subsequent trough are characteristic to the relaxation tests, regardless of cable material (at least in the range tested). The tension comparison, too, shows a common behavior of two small initial spikes before reaching the steady-state level, as shown in Figure 19. These latter two figures show that the experimental results for this type of test were insensitive to the cable rigidity.

Figures 20, 21, and 22 show the corresponding results calculated by SEADYN. The nodal positions follow the relative behavior of the experiments, although the results for the nylon cable indicate a more rapid movement. The SEADYN calculated buoy velocities in Figure 21 are much different in behavior from the experimental velocities, but are similar in behavior to each other. These displacement and velocity errors are not considered significant due to the approximate nature of the default drag coefficients used for both the sphere and the cable. The similarities in the buoy velocity histories do indicate a consistency in the SEADYN analyses. Tensions calculated by SEADYN (Figure 22) do not model the actual tensions very well, especially for the stiff nylon line.

Figures 23, 24, and 25 show the comparisons between Tests 8 and 9 as modelled by SNAPLG. The comparison for Test 7 was not made on SNAPLG due to the close behavior between Tests 7 and 8 in both the experimental and SEADYN results. The nodal positions in Figure 23 show the same relationships as those in Figure 17 for the experimental results. The velocities in Figure 24, however, are too smooth compared to the actual results. The same is true for the SNAPLG tensions plotted in Figure 25 when compared to the experimental tensions shown in Figure 19.

Summary of Single Point Mooring Comparisons

A total of 5 mooring relaxation comparisons were made. SEADYN and SNAPLG performed well for this type of test, although both models predicted free-end velocities and fixed-end tensions much smoother than the experimental values. This smoothing-out could be an important discrepancy if acceleration or snap load estimates were needed.

The models showed the poorest comparisons for Test 9, which involved the nylon line. SEADYN tensions, specifically, were poor for this test. The closest agreement between the calculated and experimental results was for the taut cable initial condition test (Test 19).

SIMULATED ANCHOR-LAST DEPLOYMENT COMPARISONS

Test 32

The comparisons for this test were expected to be the best among the anchor-last tests because of the relatively taut initial shape and the soft cable material (see Simulation Model Abstracts section). As shown in Figures 26, 27, and 28, both models calculated values close to the measured. For both the anchor velocities and tensions, SEADYN's results model the experimental behavior closer than SNAPLG.

Test 35

Since a nylon cable was used in this test, both models were expected to give only approximate results. This was true only for SNAPLG; SEADYN performed well. As shown in the nodal position comparison in Figure 29, SEADYN's calculations agree well, while SNAPLG's calculations are very erratic (note the position of the anchor relative to the cable at t = 0.5 seconds). The same analysis holds true for the velocities shown in Figure 30. The differences between the tension calculations shown in Figures 31a and 31b are even greater than expected from the previous figures; SEADYN's tension history is excellent, while SNAPLG's tensions are wild and unstable.

Test 39

This is the last anchor-last test for which a complete comparison was made. The nodal position comparison (Figure 32) and anchor velocity comparison (Figure 33) again show that SNAPLG had trouble modelling the behavior (note anchor position at t = 0.9 seconds). Both models performed satisfactorily with the tension calculations as shown in Figure 34, but SEADYN simulated the initial tension spike whereas SNAPLG did not.

Test 43

This test was chosen for the comparisons because of the strong oscillations present in the experimental tensions. Although the performance of both models worsens as the initial shape becomes more slack, it was hoped that the lack of any tension spikes might allow for good predictions nonetheless. This was not the case, however, as shown in Figure 35. Neither model predicted the response and only SNAPLG stayed close in magnitude.

Test 46

This test was also chosen because it showed a distinctive experimental tension history (i.e., a large singular initial spike), and for the fact that it represented a difficult test for the models with a stiff nylon cable and the slackest initial cable shape of all the anchor-last comparisons. As shown in Figure 36, SEADYN could not produce tensions close to the experimental. SNAPLG was not tested after its performance with nylon cable in Test 35.

Summary of Anchor-Last Comparisons

A total of 5 simulated anchor-last deployments were tested. As with the single point mooring relaxation tests, SEADYN and SNAPLG performed best for initially taut anchor-last deployments with soft cables. Neither model performed satisfactorily for the slack tests.

It should be noted that the SNAPLG results for Test 35 represent the best results chosen from several simulation runs. The initial SNAPLG model had lumped masses in the same locations as the nodes in SEADYN; this was the modelling technique followed in all the SNAPLG comparisons. This initial model did not produce realistic results - the anchor quickly dropped down and in too far compared to the experimental data and SEADYN calculations. Further runs were made with SNAPLG, with the final model using two additional "half" lumped masses at the end of the cable. The changes did not produce any significant improvements. Also, for the nylon cables in this and other tests, SNAPLG could not converge on the static solution, which probably accounted for much of the dynamic instabilities.

BI-MOOR RELAXATION COMPARISONS

Test 60

This test was an out-of-plane test, and could not be modelled by the two-dimensional SNAPLG. Figure 37, however, shows the comparison between the experimental and SEADYN tension histories. The calculated tensions from SEADYN are extremely unstable, and show no tendency to stabilize even after 3.5 seconds. This instability was not surprising since a stiff cable was used.

Test 61

This test is similar to Test 60, except that a silicone rubber cable was used in place of the nylon cable. The tension comparison is shown in Figure 38. SEADYN tensions still show an oscillation about the steady-state value even for this softer cable material.

Summary of Bi-Moor Comparisons

Only two bi-moor relaxation comparisons were made, and both were out-of-plane tests. Because these tests were three-dimensional only SEADYN was compared.

The results were unexpected. A close fit between the experimental and SEADYN tensions was expected based on the simplicity and symmetry of the test, and the previous good comparisons for the single point mooring relaxation tests. This was not the case, however, as SEADYN never converged to a stable steady-state value.

These simulations are considered to be as good as possible from SEADYN, because the program started from its own initial equilibrium shapes and maintained a symmetry of tensions and nodal positions in both legs at all times in the dynamic analyses. A small-time step was used in the dynamic analyses and was within the proper bounds, and was not the cause of any errors. Possible causes for these instabilities are discussed in the conclusions.

SINGLE CABLE SUSPENDED LOAD COMPARISONS

Test 67

For this and the remaining comparisons only steady-state tensions are given. Experimental results were taken only after a long delay to allow start-up transients to die out; likewise, the computer simulations were taken only after a delay of at least three periods of oscillation. A best fit comparison was found by shifting the computer tensions in time to best match the experimental tension history.

The tension comparison for this test is shown in Figure 39. Both models calculated reasonable tensions compared to the actual values.

Test 68

The tension comparison for this test is shown in Figure 40. SEADYN tensions match the actual tensions extremely well; SNAPLG tensions do not show the regularity of the experimental tensions in either time or magnitude.

Test 94

Both models show good agreement with the experimental results as shown in Figure 41. Over this time span the results of SEADYN are slightly better than those of SNAPLG.

Summary of Single Cable Suspended Load Comparisons

The results of the single and dual cable suspended load tests are interesting because they involve forced behavior of the cable/payload systems rather than free behavior as in the previous tests. The sinusoidal motions imposed on these cables are analogous (but not necessarily scaled) to the type of motion expected under actual ocean deployments of full-size systems.

Three single cable suspended load comparisons were made. The cable material was silicone rubber in all cases; different anchor sizes and frequencies of oscillation were used for each test.

The only difference between the experimental conditions of the first two tests was the forcing frequency, so a relative comparison can be made between the tensions for both tests. For this type of test the natural circular frequency (w_n) of the system can be found by:

$$w_n = \left[\frac{EA\ g}{L\ B + \frac{\Delta}{2}} \right]^{1/2} \qquad (1)$$

where
- EA = cable rigidity
- g = gravitational constant
- L = length of cable
- B = buoyancy of the anchor
- Δ = displacement of the anchor
- $\Delta/2$ = added mass of the spherical anchor

When excited at its natural frequency the response of an undamped linear system becomes unbounded. The same is not true, however, for undamped nonlinear systems because the natural frequency is a function of the response amplitude (which changes the stiffness of the system.) Thus, the behavior of the system becomes very complicated near resonance, and provides a good test for the undamped, nonlinear models in both programs (see Reference 2, page 7-32).

For these tests w_n was found to be 8.32 rad/sec, which makes the natural frequency about 79 cycles/min. This shows that both tests were conducted close to the resonant frequency of the system; in light of this the results are considered very good. In all cases the amplitude of the tension peaks is equal to the steady-state tension.

A second mode of comparison between the experimental and predicted results involves the displacements. During the experiments it was observed (in Test 67) that the oscillator and anchor were moving 180° out of phase; this behavior was duplicated in both SEADYN and SNAPLG. Both programs also showed an average amplitude of anchor motion of 2.5 in. compared to an amplitude of 1.5 in. at the top of the cable. This amplification would be expected in a system near resonance.

The results from Test 94 (Figure 41) show well-behaved tensions: the peak-to-peak amplitudes are only half the steady-state tension. For this test the forcing frequency was one-fourth of the natural frequency.

DUAL CABLE SUSPENDED LOAD COMPARISONS

Test 133

Only two tests of this type were performed, and both are included here. This test used an anchor as the suspended load; this meant that the tensions at the lower fixed end approached zero at certain times in each rotation of the top cable end during the anchor free-fall. These experimental tensions are shown in Figure 42, along with the model simulations.

As expected, both models had trouble with the small tensions during each period of rotation. This difficulty was probably due to the combined effects from two sources. The initial source of error was the lack of internal damping in the cable material, which resulted in calculated displacements (and therefore tensions) larger than the measured displacements. This fact is evident in Figure 42. A consequence of this larger amplitude of model displacements was the subsequent overshoot into the compressive region, which placed the models in an unrealistic position compared to the observed behavior. This overshoot then introduced the approximations to slack element behavior described previously which compounded the error.

Test 142

In this test, a buoy was used as the suspended load; this kept moderate tensions at the lower fixed end, so better comparisons would be expected. This is indeed true for SEADYN as shown in Figure 43. The agreement for SEADYN in this test was the best of all the comparisons, as seen by the characteristic behavior followed by both curves. SNAPLG's tension was very erratic in behavior compared to the previous curves.

Summary of Dual Cable Suspended Load Comparisons

Both models had difficulty with the near-slack conditions for test 133, but the results from SEADYN are at least reasonable. For the second test SEADYN's predicted tensions were excellent while SNAPLG's results were unexpectedly erratic.

CONCLUSIONS

SEADYN

These comparisons have shown SEADYN to be a reliable tool for modelling cable dynamics. In general, SEADYN's results showed the same behavior as observed in the experiments; except for a few tests, the magnitudes of the predicted tensions also compared well.

In the single point mooring relaxation comparisons SEADYN calculations were very reliable, except for the nylon cable test (#9). Although the calculated tensions did not show the initial tension snaploads in all the comparisons, they did have the steep initial rise not found with SNAPLG. The fact that the displacements from the model lead the experimental displacements is probably due to the use of the default drag coefficients used in the program. As these default coefficients are used as approximate values only, this is not considered to be a serious fault with the model.

The comparisons for the simulated anchor-last deployment tests showed that SEADYN is capable of producing reasonable estimates for almost all the tests. In the two slackest tests only, SEADYN's tensions are too large compared to the experimental tensions; it is interesting, though, that for all the tests SEADYN does reproduce the characteristic behavior of the tension history.

The performance of SEADYN in the bi-mooring relaxation tests was poor. In both comparisons the tensions continued to oscillate wildly about the expected steady-state value. This type of behavior might be expected for the stiff nylon cable due to model sensitivities to error bounds, etc., but not for the soft rubber cable. It is therefore assumed that these oscillations were due to the neglect of internal damping in the models. It is not assumed, however, that this model behavior would persist at larger scales, where tangential cable drag could act as a damper for long cable lengths. Many ocean cable networks are similar to the bi-mooring type of configuration, and the results from the tests at this small scale cast some doubt on the ability of SEADYN to reliably model this important class of cable structures.

In the single and dual cable suspended load comparisons SEADYN performed very well. Of the five comparisons in this last group, SEADYN predicted accurate results in four; in the fifth comparison the difference in magnitudes was still within 20%. The ability of the model to accurately predict the tensions for these last two types is important when the imposed oscillations are interpreted as imposed displacements due to surface waves.

Conclusions from these suspended load comparisons regarding the lack of internal damping in the models were not anticipated, based on the conclusions from the bi-mooring relaxation comparisons. The effects of internal damping were expected to be more significant in the suspended load tests than the bi-mooring tests because the suspended load tests involved forced dynamic responses. However, the first two single cable suspended load tests were oscillated near the natural frequency where the lack of internal damping should have been most noticeable, and for both tests the model results were good. Therefore, no conclusions can be made from these comparisons on the effects of internal damping. Test 133 on the other hand did indicate that internal damping was not negligible, at least for that set of conditions.

SNAPLG

SNAPLG's performance in these comparisons can be considered as acceptable for most tests. However, in a good number of tests SNAPLG did not produce realistic results.

In the single point mooring relaxation comparisons, SNAPLG did quite well. The slight discrepancy in displacements is probably due to the drag coefficient used (SNAPLG uses a constant value), and is easily corrected. The fact that SNAPLG did not predict tension spikes for tests 8 and 9 could cause serious problems if that behavior existed in full-sized systems. SNAPLG results for the nylon cable test (#9) were much better than SEADYN's.

In the simulated anchor-last deployments SNAPLG did not produce reliable results, especially for the nylon cable test (#35). In that comparison both the displacements and tensions from SNAPLG showed large discrepancies. In the other anchor-last tests, SNAPLG tensions compared well with the experimental tensions in magnitude; however, SNAPLG failed to simulate the initial tension spikes. This again could be an important shortcoming if this behavior existed in large systems.

No comparisons were made for the bi-mooring relaxation tests because SNAPLG is limited to two-dimensional problems.

SNAPLG's performance in the single and dual cable suspended load comparisons was inconclusive. In half of the comparisons SNAPLG calculated tensions that showed reasonable agreement (within 15-20%) with the experimental tensions; in the other half the SNAPLG tensions were not periodic in behavior, and in two comparisons exhibited large tension spikes that were twice as large in magnitude as the measured tensions. Conclusions regarding the lack of internal damping are discussed with SEADYN's summary in the previous section.

General

The overall performance of these programs in the comparisons included in this report shows that finite element and lumped-mass models are both useful in predicting the responses of underwater cable structures. In most of the comparisons the predictions from both models are considered to be sufficiently accurate (±10%) in both magnitude and behavior for most engineering purposes.

These comparisons have led to some conclusions regarding the limitations of both programs. A few general remarks are applicable to both programs:

(1) Instabilities arise when relatively stiff, short segments are used. SNAPLG in particular could not converge on static solutions for such segments.

(2) Reliability of the results decreases as the cables become more slack; the model results often become unreliable when segments are completely slack.

(3) In some tests an approximate initial shape was adequate to start the dynamic analysis, but in many tests even a calculated static shape did not improve the dynamics. Using the static analysis option is recommended for all applications.

(4) Both programs had some difficulty simulating velocity and tension spikes. In general only SEADYN produced reasonable tension histories when spikes (e.g. snap loads) were involved; SNAPLG usually produced a smooth tension rise. Neither program predicted velocity spikes similar to those measured in the experiments.

These comparisons have shown that SEADYN predicted the experimental behavior more reliably than SNAPLG, although both models were shown to be useful tools in simulating the behavior of underwater cable structures. A summary of their performance in these comparisons is shown in Table 4.

RECOMMENDATIONS

The comparisons made in this study have provided a good test of the capabilities of both programs. However, because of the limited number of comparisons and the small scale of the tests, this study cannot be regarded as a conclusive test of the validity of either program. Rather, the conclusions of this study can be used, along with future comparisons, to provide a comprehensive check on the reliability of both models.

These comparisons are also valuable in suggesting directions for future studies. These recommendations are:

(1) A further investigation of drag coefficients should be made, including both the cable and payload (sphere). The effect of these coefficients on both programs should also be studied.

(2) Some of the remaining experimental results from this 6-ft cable experiment should be used in comparisons, especially the bi-moor relaxations. Only 1/4 of the 67 tests were selected for this study.

(3) The results of this and future studies should be used to better define the conditions that cause unrealistic behavior in the models; terms such as "slack" and "stiff" should be defined so that these conditions can be identified for applications on any scale.

(4) Model sensitivities to input parameters should be used to help identify and resolve problems in the computer models. For example, the usual displacement error bounds for SEADYN were decreased by a factor of 15 for a re-run of tests 7 and 9. In test 9 the erratic behavior of the previous SEADYN tensions was eliminated, and the agreement with the measured tensions became closer. For test 7, however, the tensions became more erratic than with the original error bounds. Inconsistencies such as this must be better understood before model results can be used with confidence.

(5) Specific shortcomings of the model behavior identified in these comparisons should be closely investigated in future studies. Some of these shortcomings could cause serious problems if they persist at all scales.

The most serious of these shortcomings is the inability of the models to simulate the initial tension spikes (snap loads) in many of these tests. Prediction of these large spikes and accompanying accelerations would be critical for sizing hardware requirements in actual applications.

(6) The effects of internal damping should also be studied in future investigations, as indicated by the conclusions from this report.

REFERENCES

1. Meggitt, D. J., Palo, P. A., and Buck, E. F. "Small-Size Laboratory Experiments on the Large-Displacement Dynamics of Cable Systems, Volume I," CEL Technical Memorandum M-44-78-11, Jun 1978.

2. Webster, R. L. "An Application of the Finite Element Method to the Determination of Nonlinear Static and Dynamic Responses of Underwater Cable Structures," Ph D thesis, Cornell University, Ithica, N.Y., Jan 1976. Also available as General Electric Co. Report TIS R76EMH2, Jan 1976.

3. Liu, F. C. "Snap Loads in Lifting and Mooring Cable Systems Induced by Surface Wave Conditions," NCEL Technical Note N-1288, Port Hueneme, Calif., Sep 1973.

4. Meggitt, D. J., Palo, P. A., Buck, E. F., and Lacroce, P. "Small-Size Laboratory Experiments on the Large Displacement Dynamics of Cable Systems, Volumes II-A Through II-D," CEL Technical Memorandum M-44-79-1, Oct 1978.

Table 1. Buoy, Anchor, and Cable Properties

BUOYS

Diameter	2.0 in.
Weight in air	0.025 lb
Weight in water	-0.121 lb

ANCHORS

	Diameter	Weight in Air	Weight in Water
0.1 lb Anchor	2.0 in.	0.246 lb	0.108 lb
0.25 lb Anchor	2.0 in.	0.398 lb	0.252 lb

CABLES

	Diameter	Weight in Air	Weight in Water
Silicon w/Wire	0.163 in.	11.443×10^{-3} lb/ft	2.381×10^{-3} lb/ft
Silicon	0.163 in.	8.979×10^{-3} lb/ft	1.075×10^{-3} lb/ft
Nylon	0.1 in.	3.736×10^{-3} lb/ft	1.057×10^{-3} lb/ft

Table 2. Index to Comparisons

Type of Test	Test Number	Initial Position of Free-End		Type of Cable[1]	Load[2]	Type of Comparison[3]		
		X (in.)	Z (in.)			Displacement	Velocity	Tension
Buoy Relaxation	6	51	51	SR	B	SEA, SN	SEA	SEA
	7	51	42	SR	B	SEA	SEA	SEA
	8	51	42	RC	B	SEA, SN	SEA, SN	SEA, SN
	9	51	42	N	B	SEA, SN	SEA, SN	SEA, SN
	19	42	58.4	RC	B	SEA, SN	SEA, SN	SEA, SN
Anchor-Last	32	66	0	SR	0.1A	SEA, SN	SEA, SN	SEA, SN
	35	66	0	N	0.25A	SEA, SN	SEA, SN	SEA, SN
	39	54	0	SR	0.1A	SEA, SN	SEA, SN	SEA, SN
	43	48	0	SR	0.25A	-	-	SEA, SN
	46	42	0	N	0.1A	NR	NR	SEA
Bi-Moor Relaxation	60	42	42	N	B	NR	NR	SEA
	61	42	42	SR	B	NR	NR	SEA

continued

Table 2. Continued

Type of Test	Test Number	Free-End Oscillation		Type of Cable[1]	Load[2]	Type of Comparison[3]		
		Range (in.)	Frequency (cycles/min)			Displacement	Velocity	Tension
Single Cable Suspended Load	67	3	80	SR	0.25A	NR	NR	SEA, SN
	68	3	72	SR	0.25A	NR	NR	SEA, SN
	94	6	30	SR	0.1A	NR	NR	SEA, SN
Dual Cable Suspended Load	133	6	45	SR	0.1A	NR	NR	SEA, SN
	142	6	50	SR	B	NR	NR	SEA, SN

[1]SR = solid rubber; RC = rubber with conductors; N = nylon.

[2]B = buoy; 0.1A = 0.1 lb anchor; 0.25A = 0.25 lb anchor.

[3]SEA = SEADYN; SN = SNAPLG; NR = no experimental results.

Table 3. Default Drag Coefficients Used in SEADYN

Spherical Bodies

Reynolds Number, $R_e = \frac{V\,d}{v} = \frac{\text{Velocity x body diameter}}{\text{kinematic viscosity}}$

$C_D = 0$ for $R \leqq 0.1$

$C_D = 0.044 + 13.46/(R_e)^{0.5}$ for $0.1 < R_e \leqq 1{,}000$

$C_D = 0.47$ for $1{,}000 < R_e \leqq 10^5$

$C_D = 0.12$ for $R_e > 10^5$

Cylindrical Bodies and Cable Elements

$R_e = \frac{V_N\,d}{v} = \frac{\text{Normal Velocity x body diameter}}{\text{kinematic viscosity}}$

$R_{eT} = \frac{V_T\,d}{v} = \frac{\text{Tangential Velocity x body diameter}}{\text{kinematic viscosity}}$

$C_N = 0$ for $R_e \leqq 0.1$

$C_N = 0.45 + 5.93/(R_e)^{0.33}$ for $0.1 < R_e \leqq 400$

$C_N = 1.27$ for $400 < R_e \leqq 10^5$

$C_N = 0.3$ for $R_e > 10^5$

$C_T = 0$ for $R_{eT} \leqq 0.1$

$C_T = 1.88/(R_{eT})^{0.74}$ for $0.1 < R_{eT} \leqq 100.55$

$C_T = 0.062$ for $R_{eT} > 100.55$

Table 4. Summary of Model Vs Experimental Results

Configuration	Type of Test[1]	Reference Figures	Experimental Results Vs:[2]	
			SEADYN	SNAPLG
Single Point Mooring Relaxation	Slack	1-13	G - rubber cable P - nylon cable	S = all tension histories too smooth
	Taut	14-16	G	G
Simulated Anchor-Last Deployment	Slack	32-36	P - magnitude of the initial tension spike too large	P - all tension histories too smooth
	Taut	26-31	G	S - rubber cable P - nylon cable
Bi-Mooring Relaxation	Slack	37, 38	P - no damping of tension oscillations in both cables	No comparison
Single Cable Suspended Load	-	39-41	G	S - high frequency excitation G - low frequency excitation

continued

Table 4. Continued

Configuration	Type of Test[1]	Reference Figures	Experimental Results Vs:[2]	
			SEADYN	SNAPLG
Dual Cable Suspended Load	Buoy	43	G	P - peak tensions too large
	Anchor	42	P - excessive slack compared to experiment	P - peak tensions too large, excessive slack

[1]Type of test - based on initial configuration/tension.
[2]G = good; S = satisfactory; P = poor.

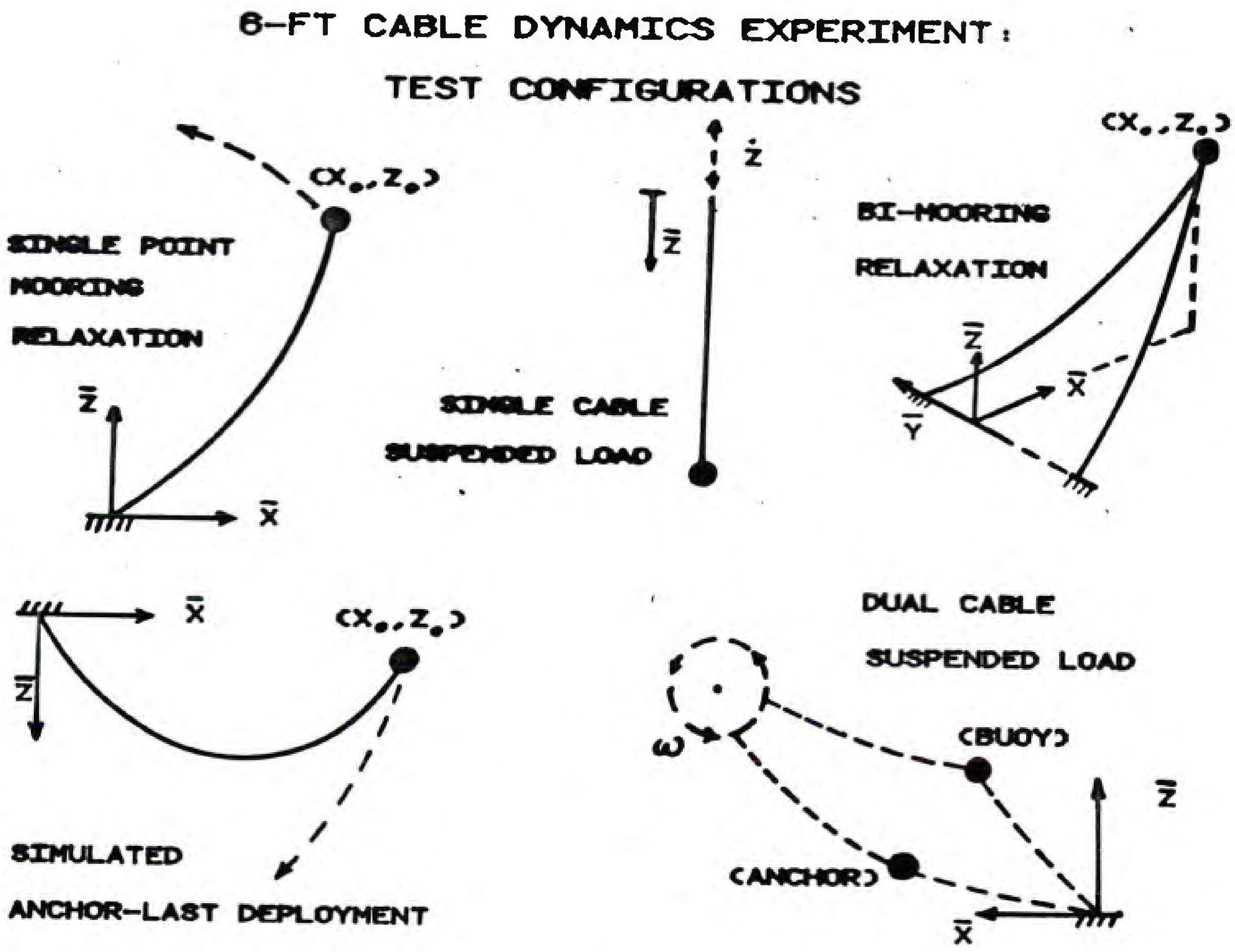

FIGURE 1. TEST CONFIGURATIONS.

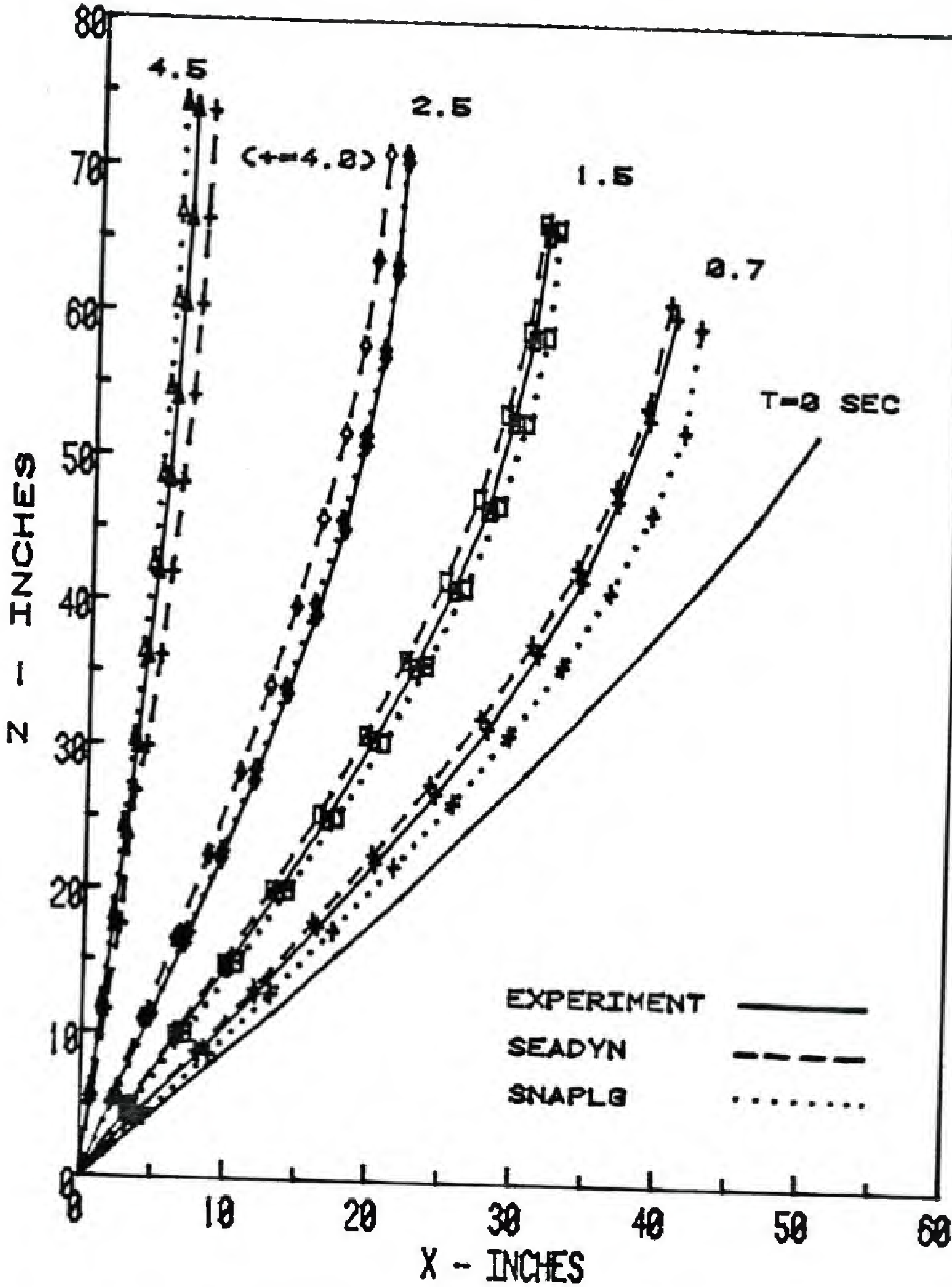

FIGURE 2. DISPLACEMENT COMPARISON FOR TEST #6.

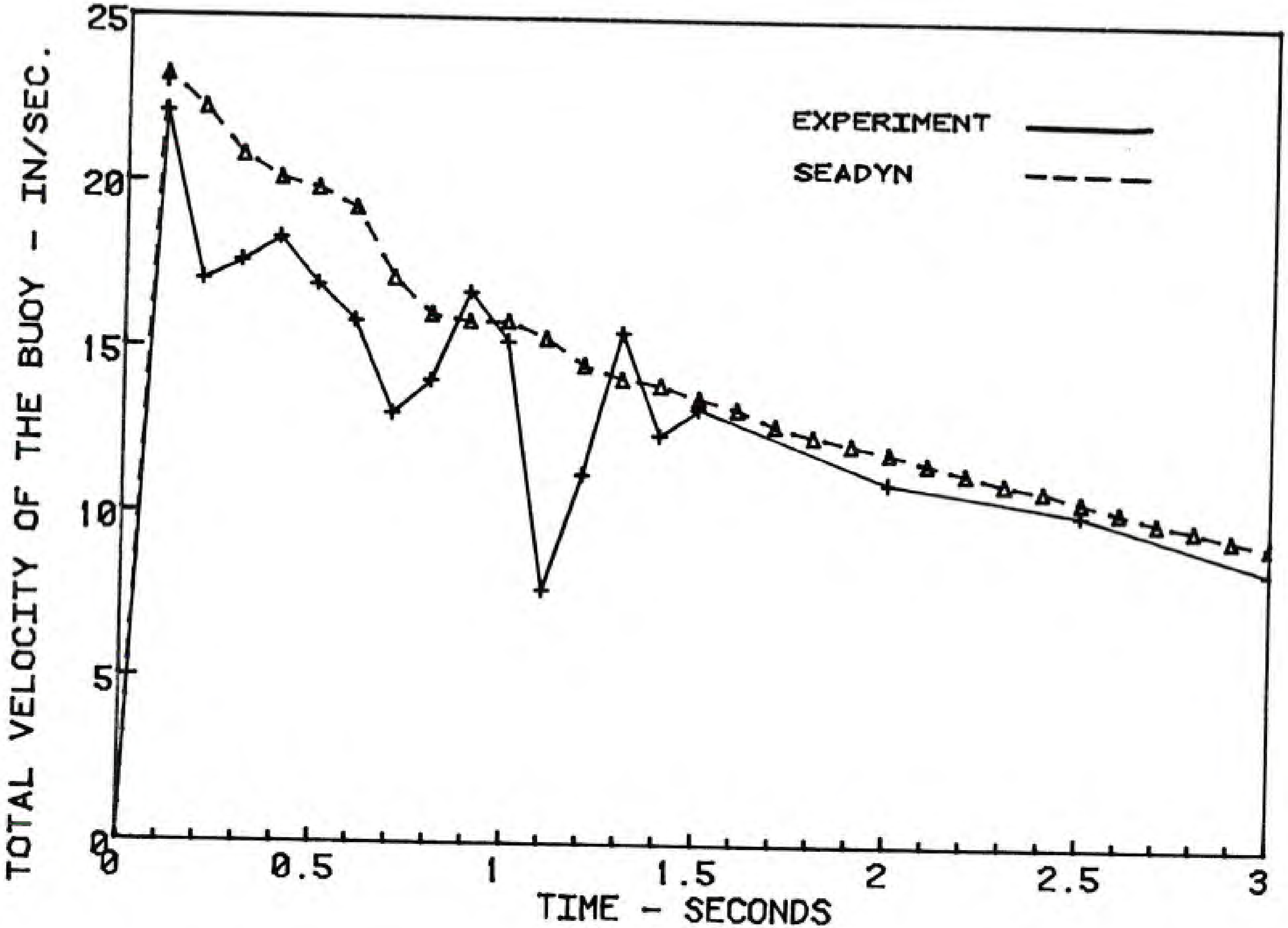

FIGURE 3. BUOY VELOCITY COMPARISON FOR TEST #6.

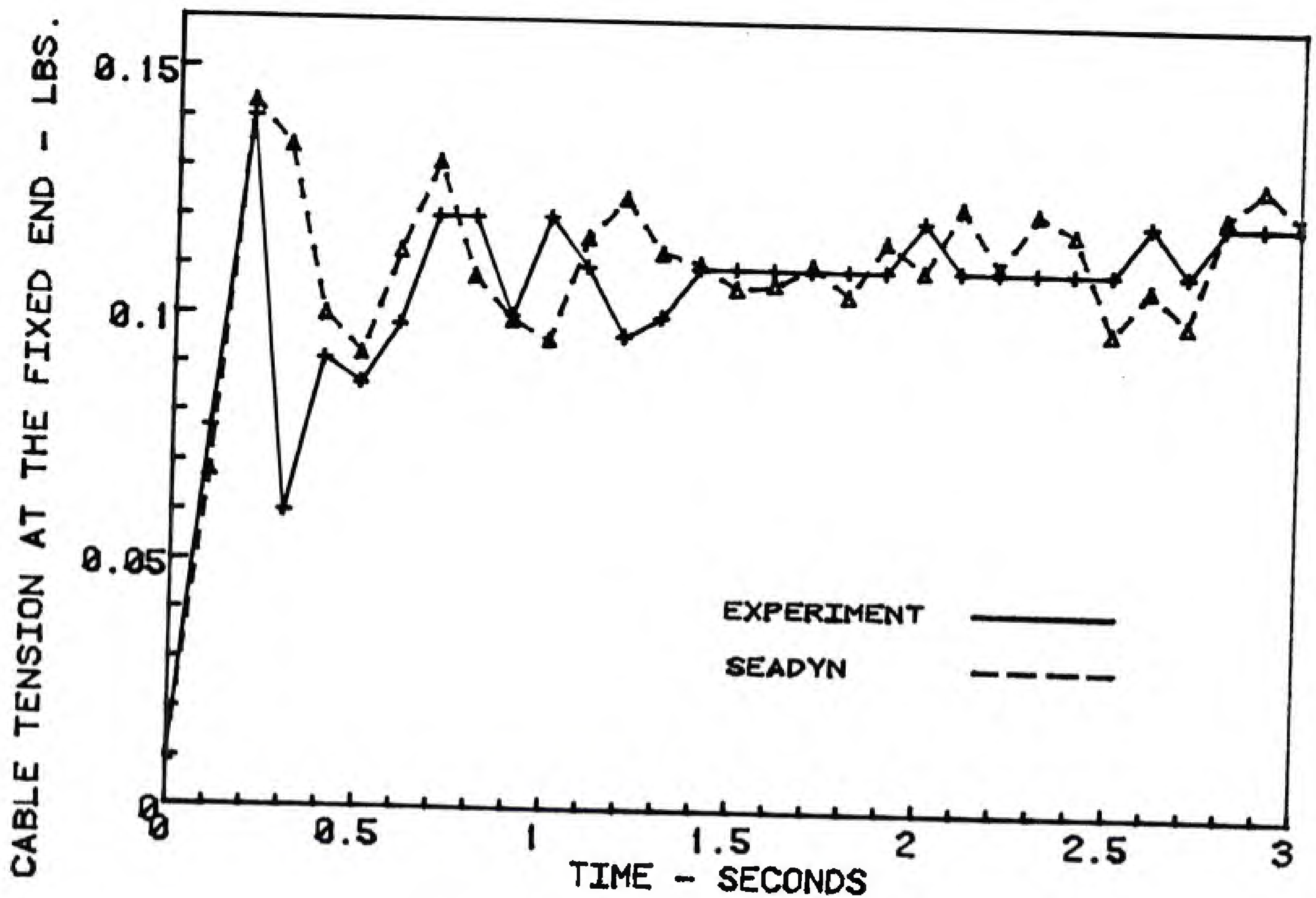

FIGURE 4. TENSION COMPARISON FOR TEST #6.

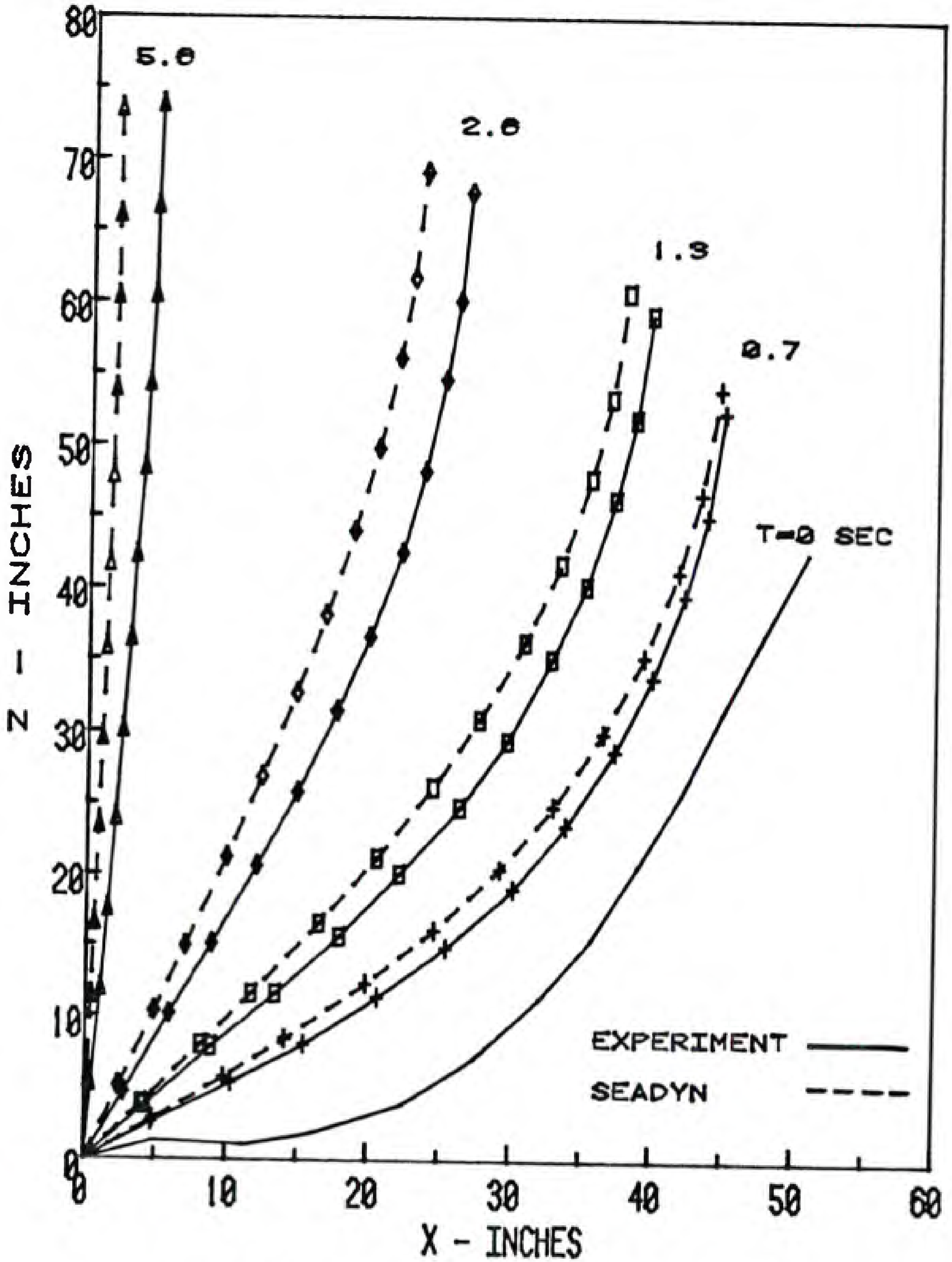

FIGURE 5. DISPLACEMENT COMPARISON FOR TEST #7.

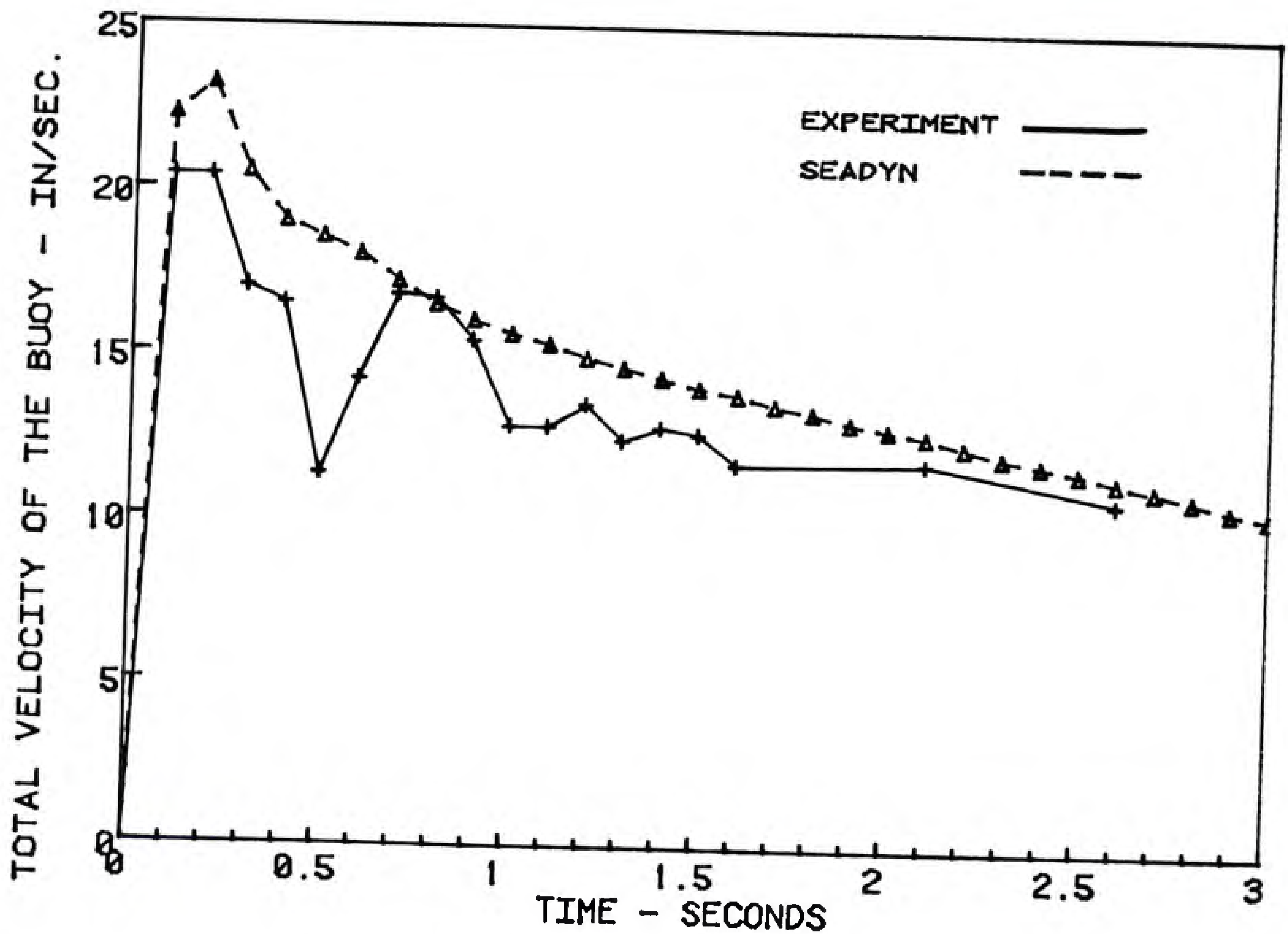

FIGURE 6. BUOY VELOCITY COMPARISON FOR TEST #7.

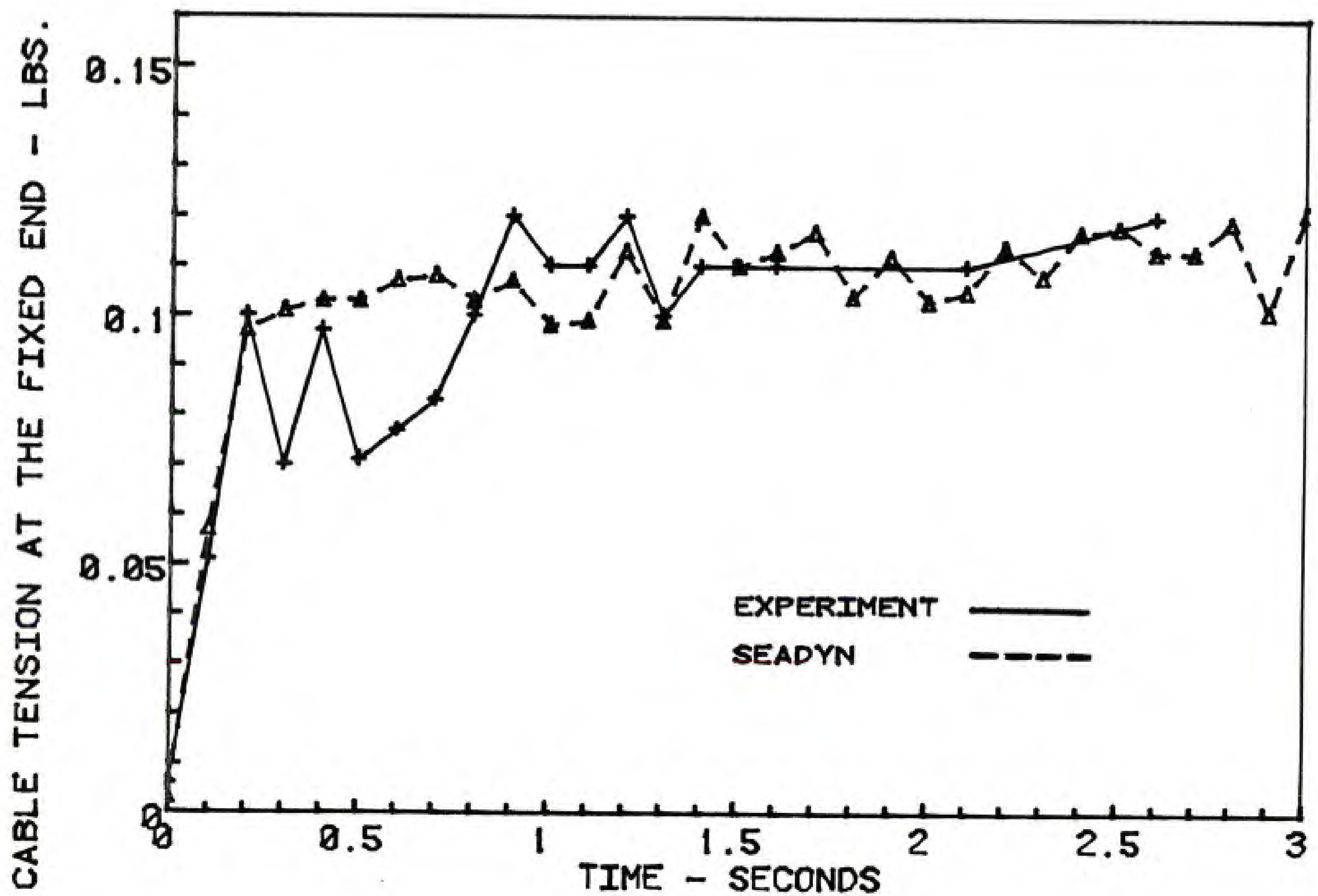

FIGURE 7. TENSION COMPARISON FOR TEST #7.

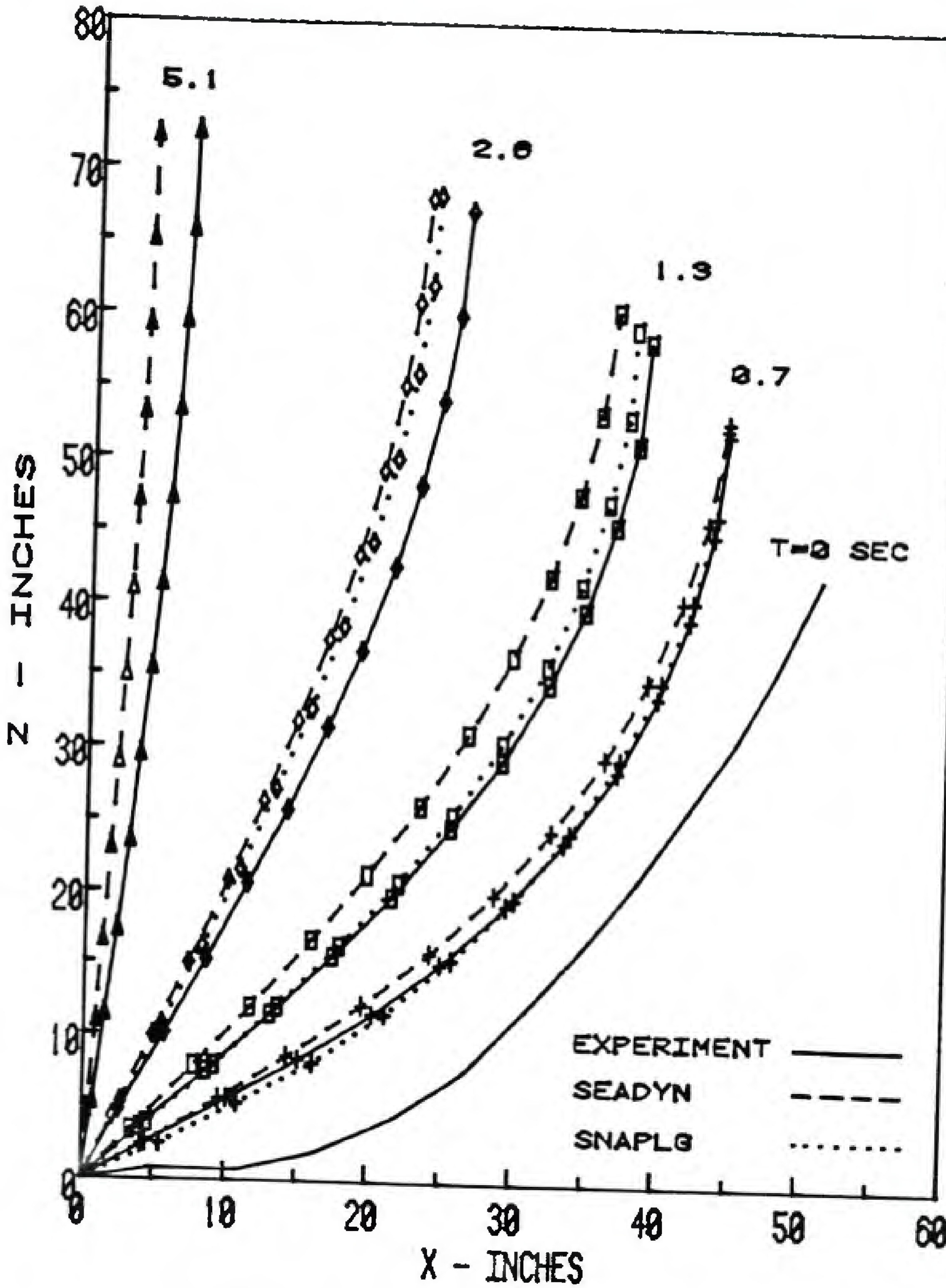

FIGURE 8. DISPLACEMENT COMPARISON FOR TEST #8.

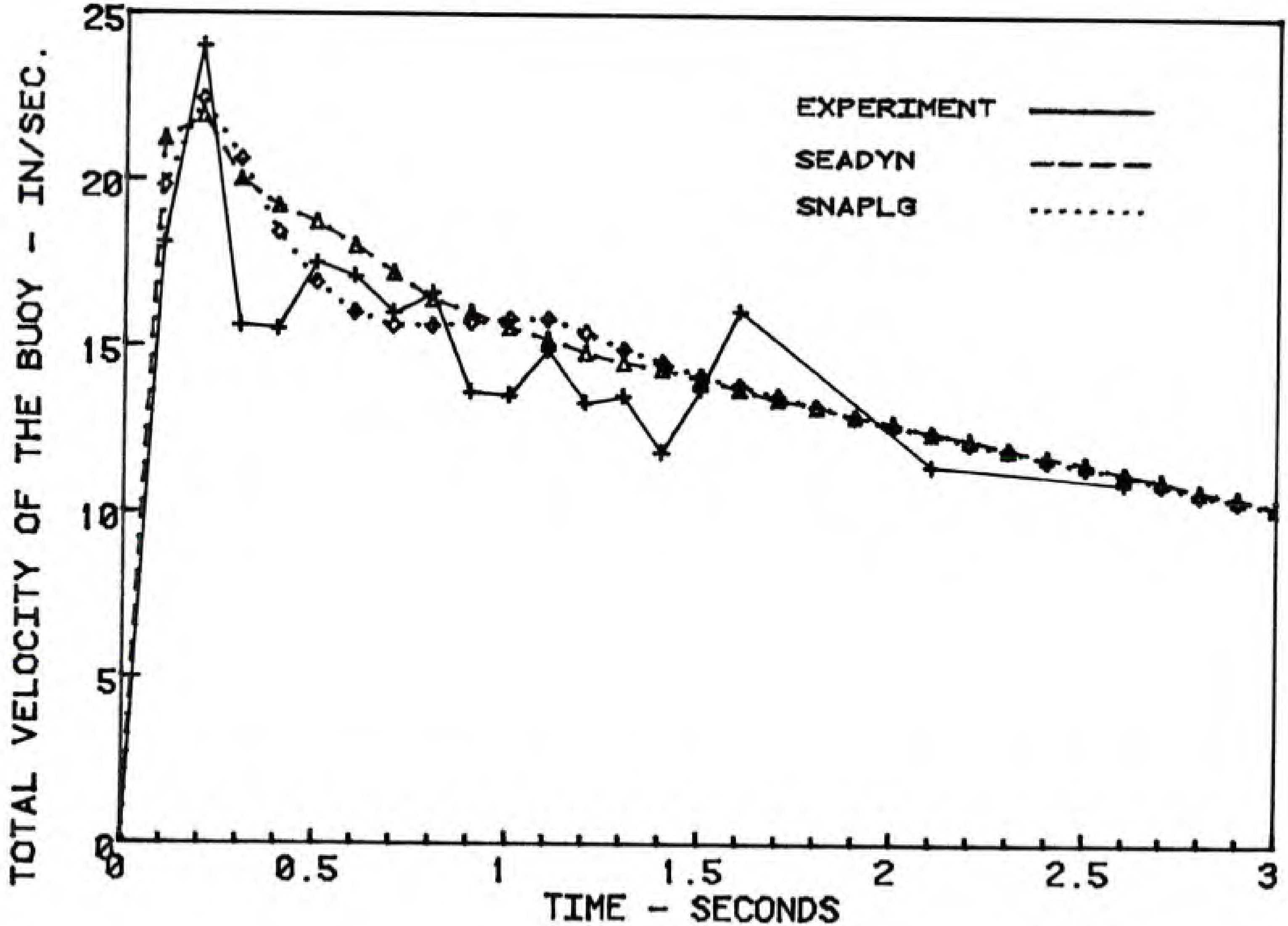

FIGURE 9. BUOY VELOCITY COMPARISON FOR TEST #8.

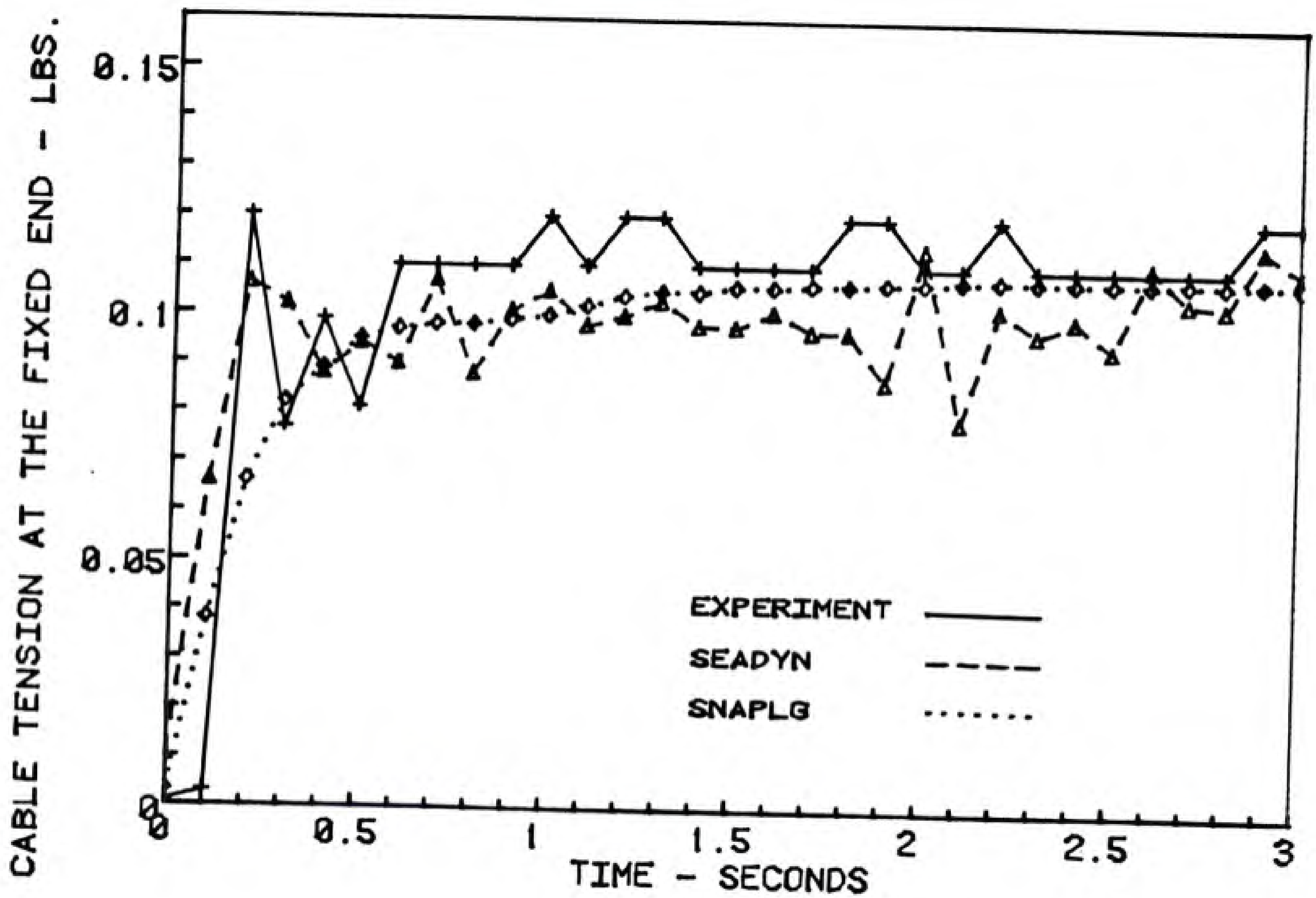

FIGURE 10. TENSION COMPARISON FOR TEST #8.

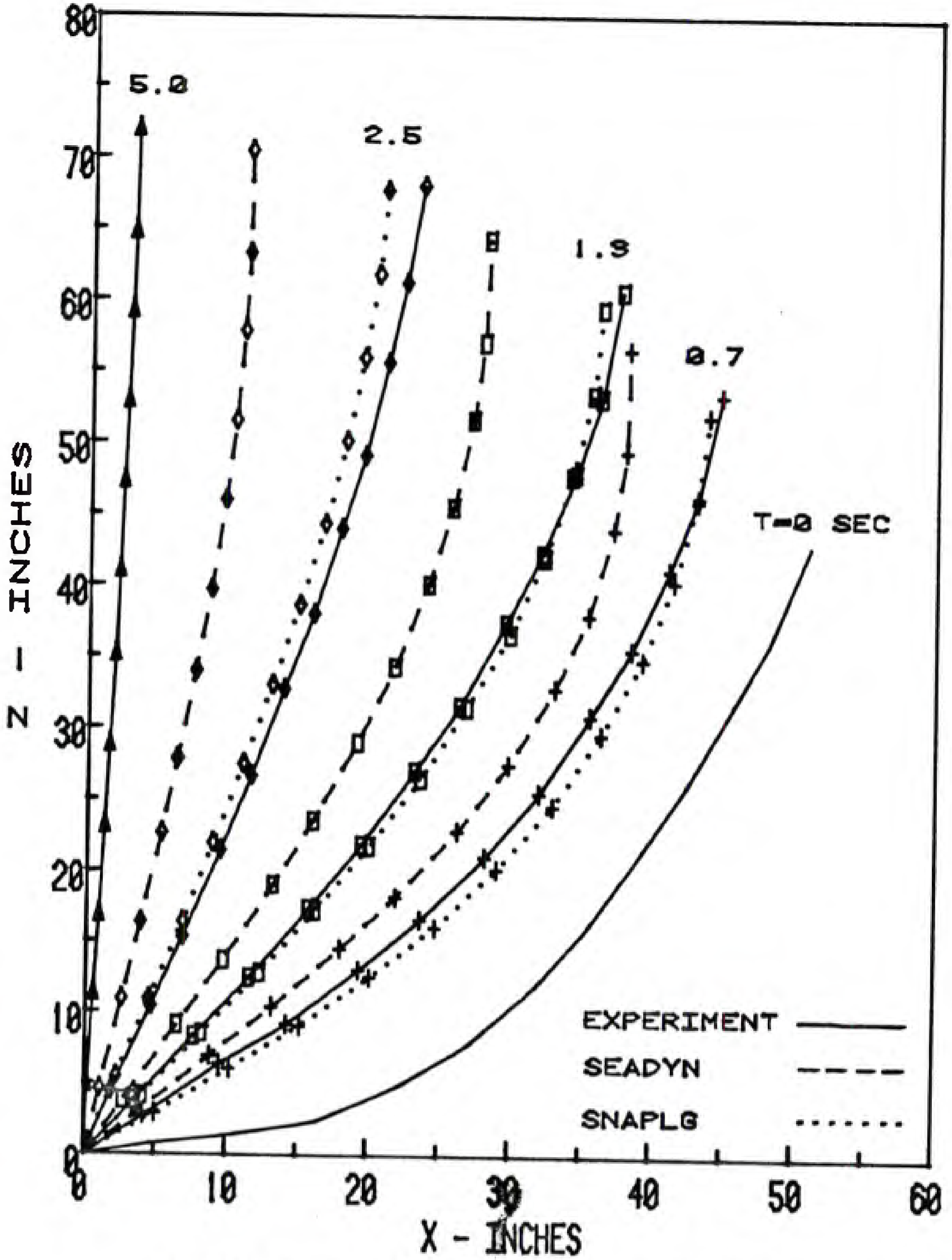

FIGURE 11. DISPLACEMENT COMPARISON FOR TEST #9.

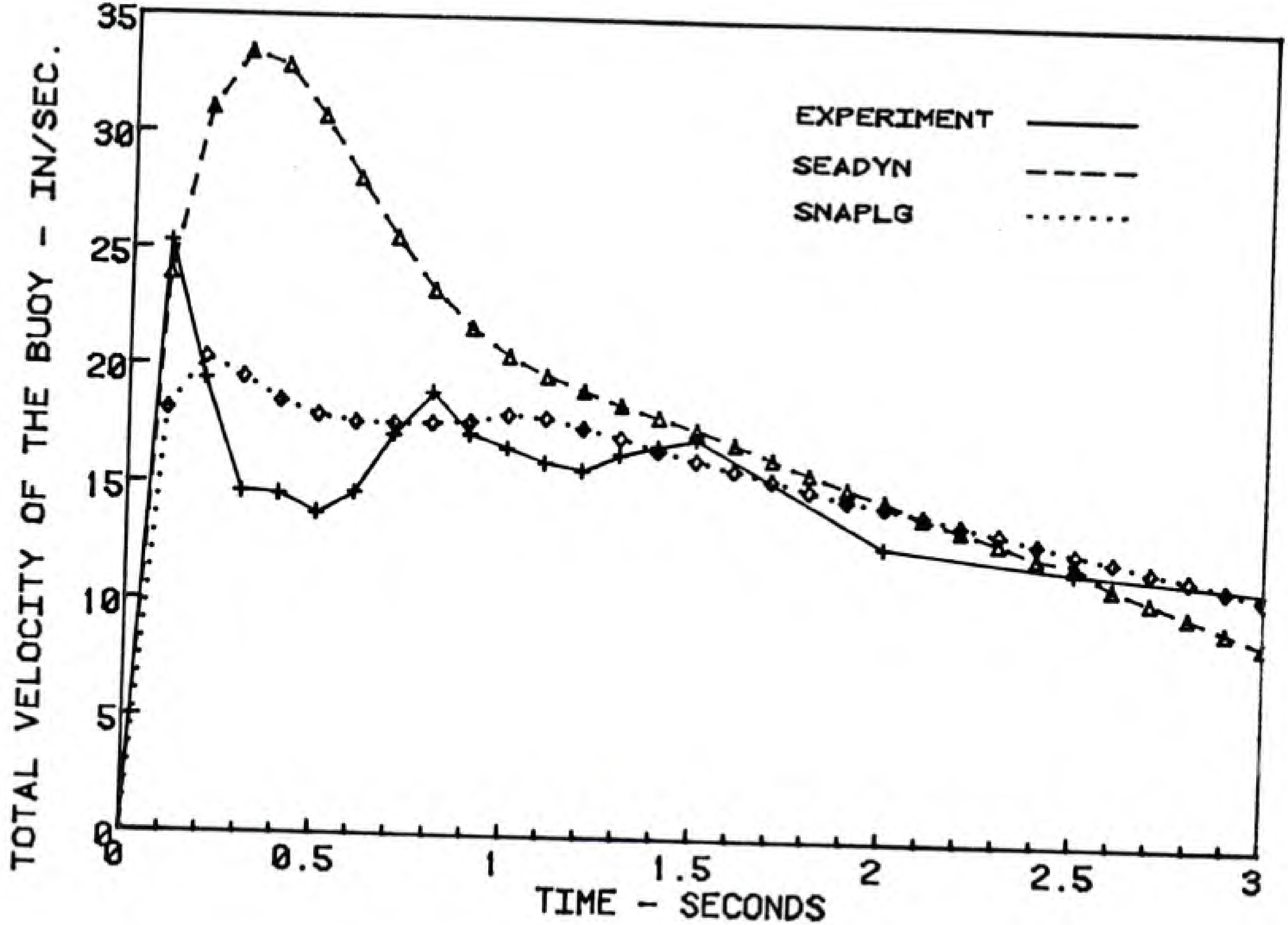

FIGURE 12. BUOY VELOCITY COMPARISON FOR TEST #9.

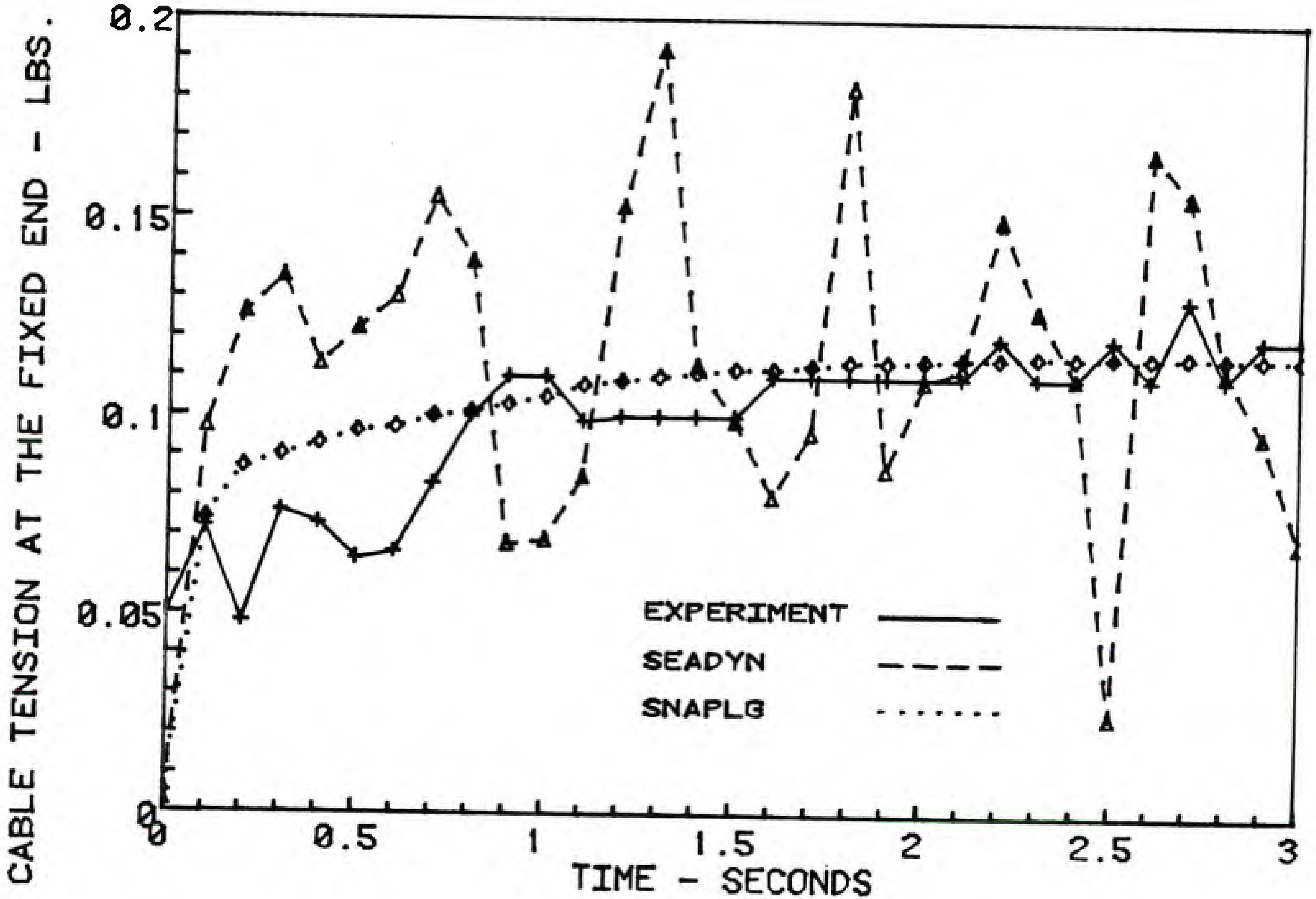

FIGURE 13. TENSION COMPARISON FOR TEST #9.

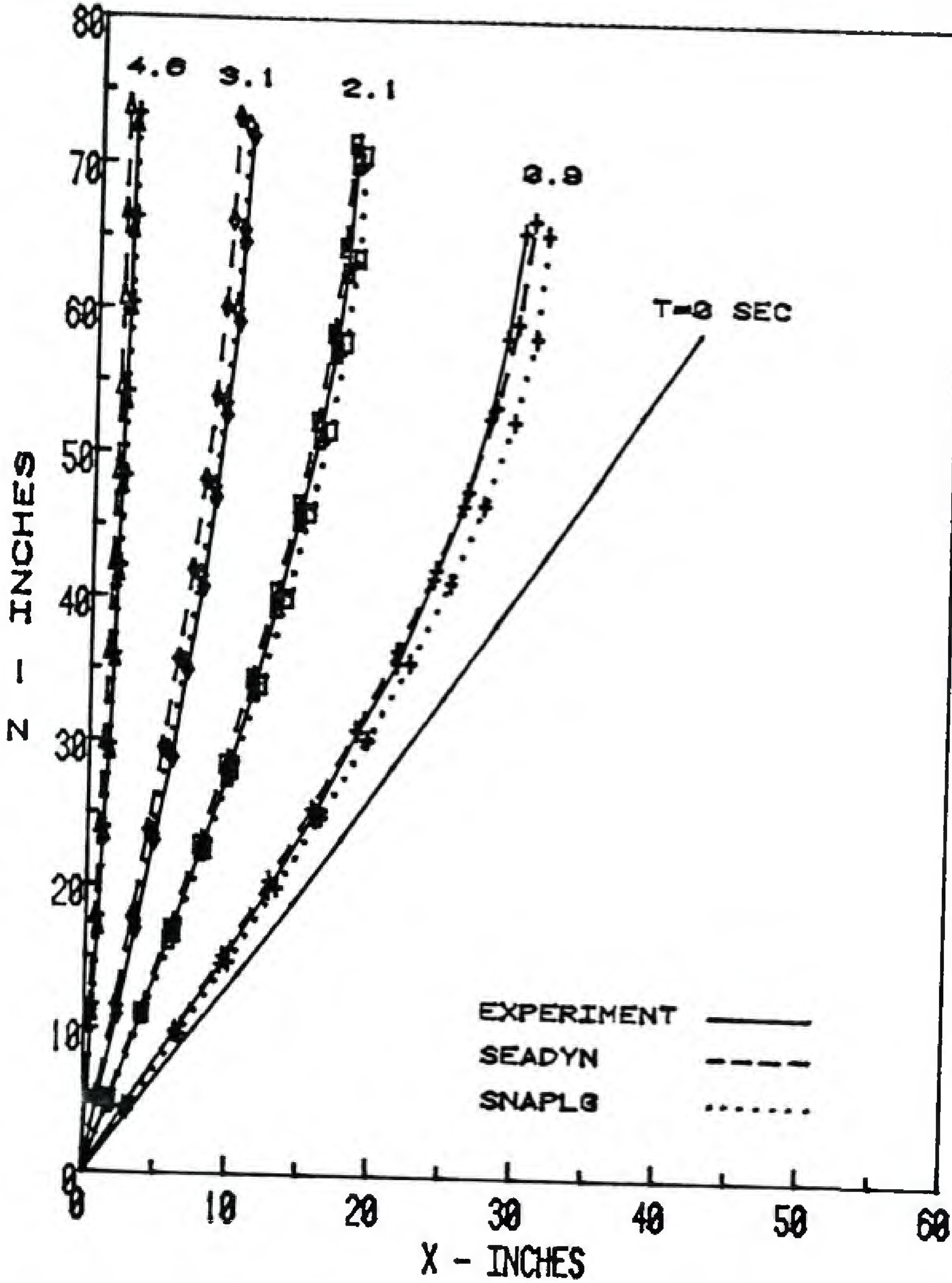

FIGURE 14. DISPLACEMENT COMPARISON FOR TEST #19.

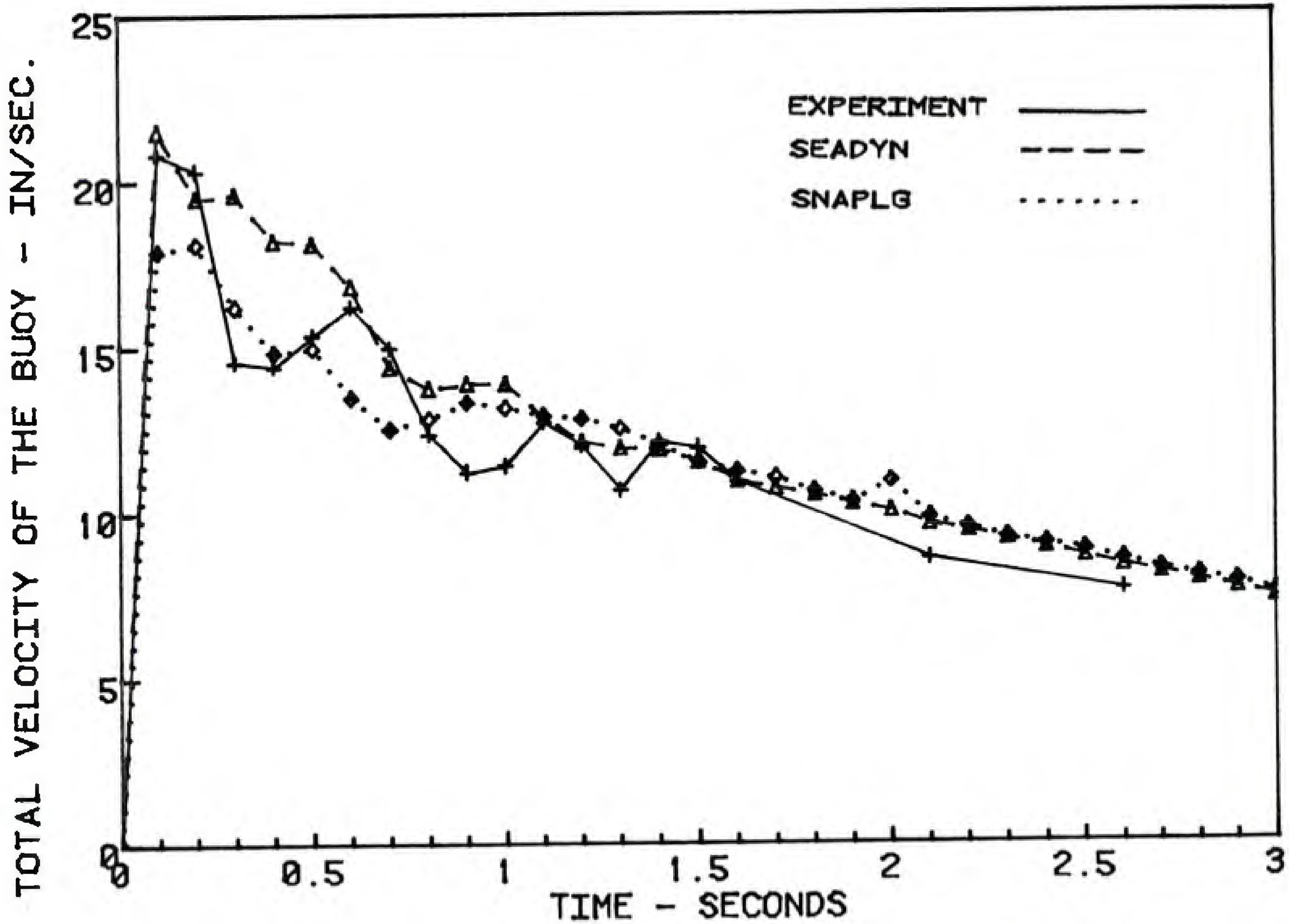

FIGURE 15. BUOY VELOCITY COMPARISON FOR TEST #19.

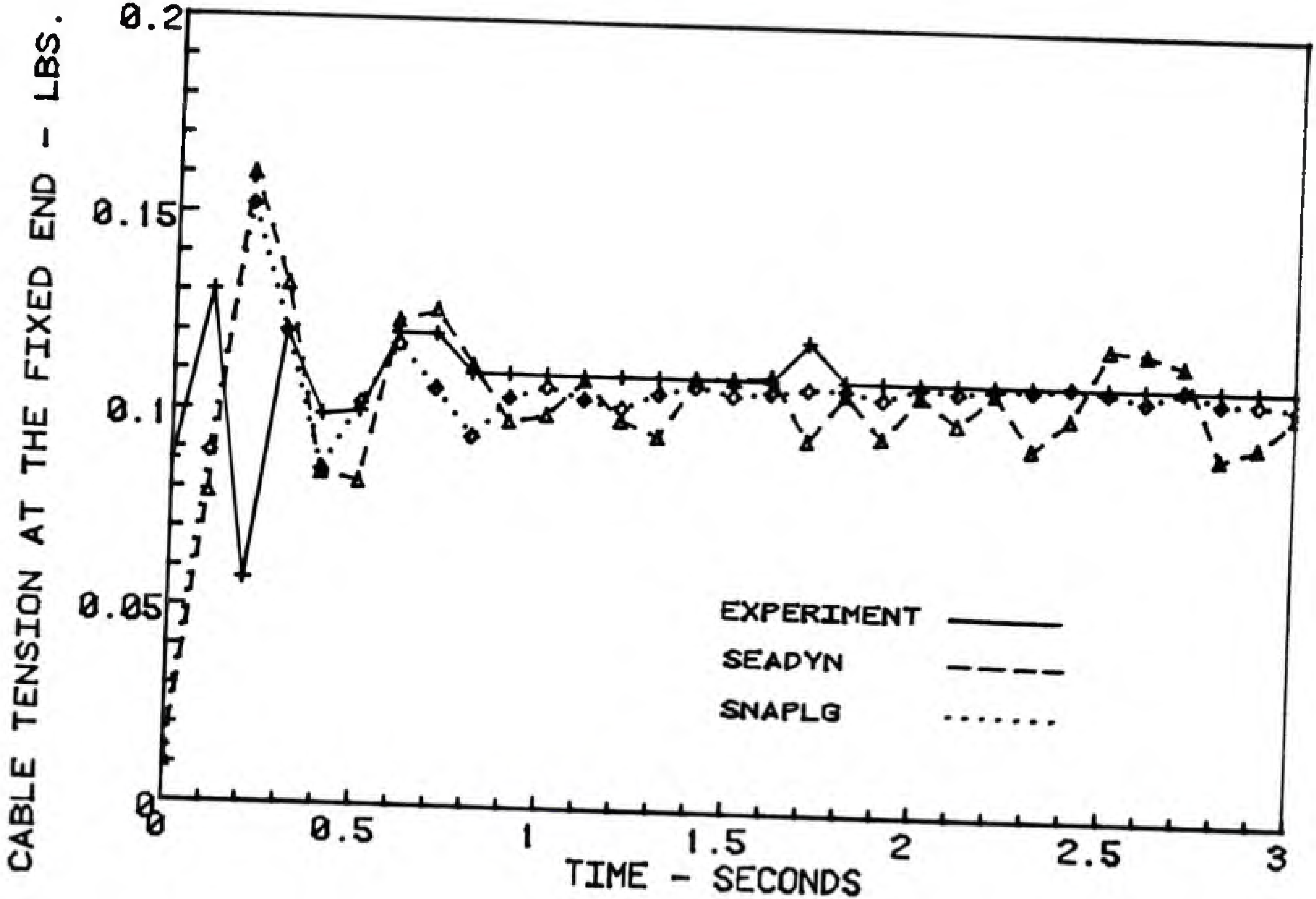

FIGURE 16. TENSION COMPARISON FOR TEST #19.

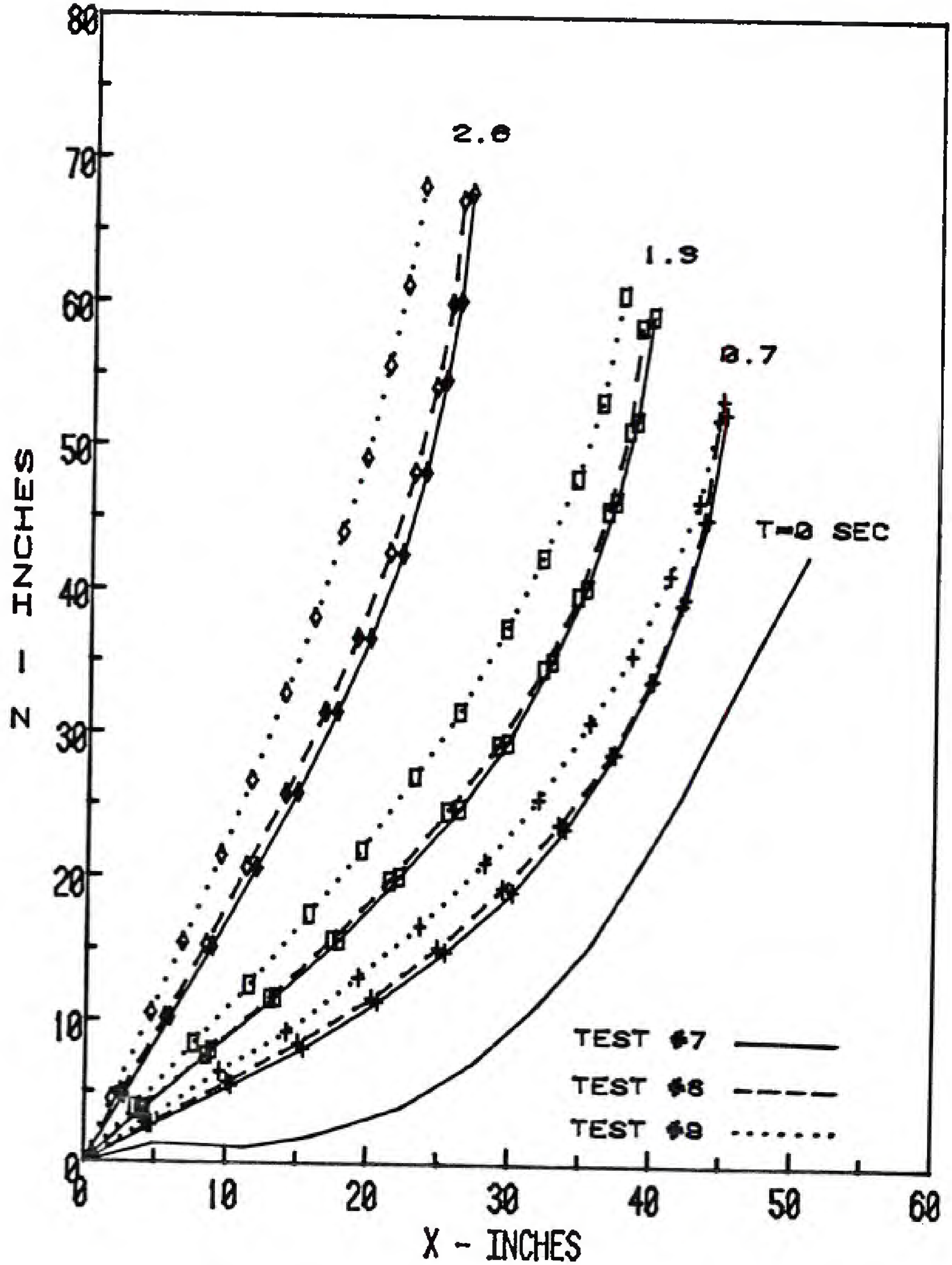

FIGURE 17. EXPERIMENTAL DISPLACEMENT COMPARISON FOR TESTS #7, #8, AND #9.

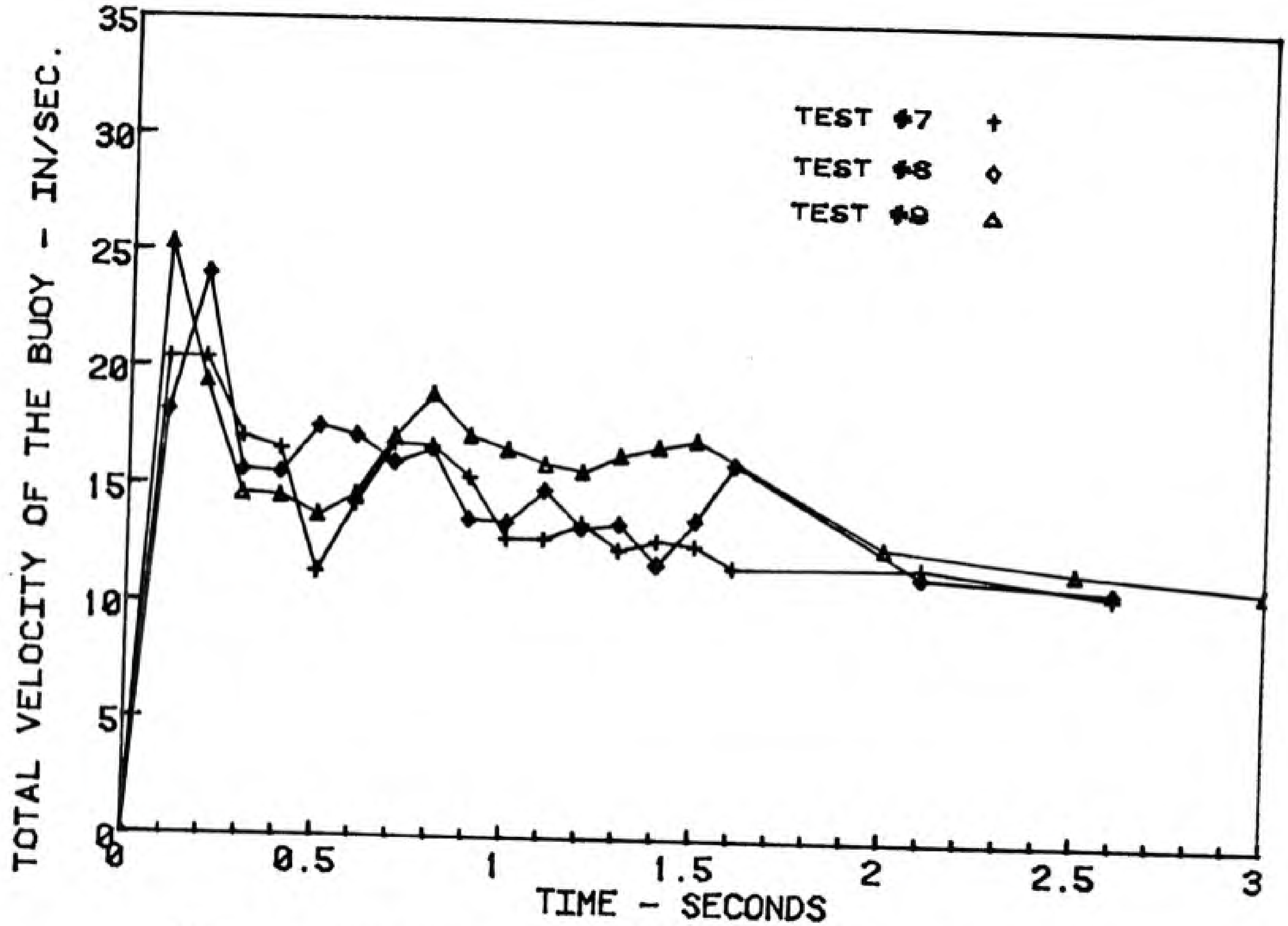

FIGURE 18. EXPERIMENTAL BUOY VELOCITY COMPARISON FOR TESTS #7, #8, AND #9.

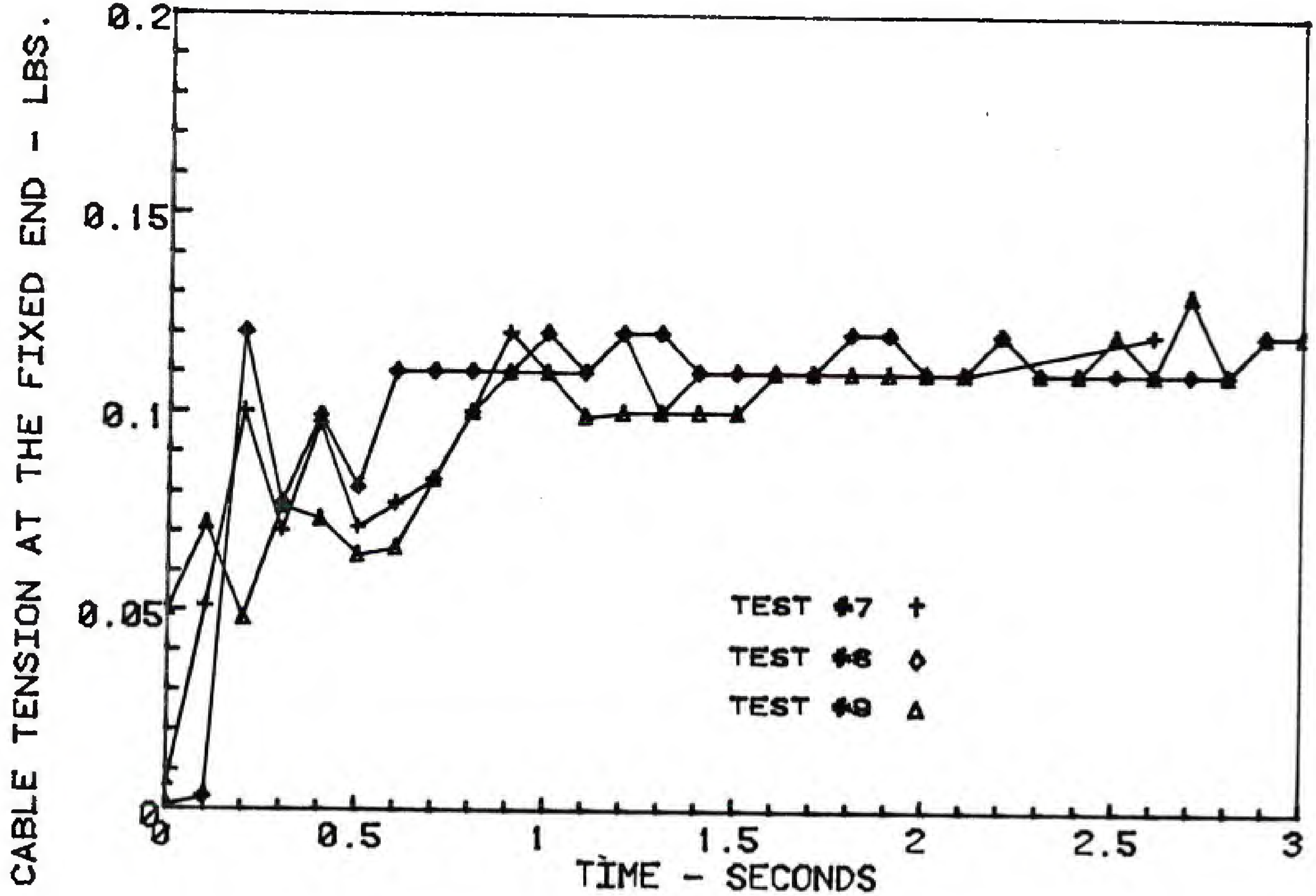

FIGURE 19. EXPERIMENTAL TENSION COMPARISON FOR TESTS #7, #8, AND #9.

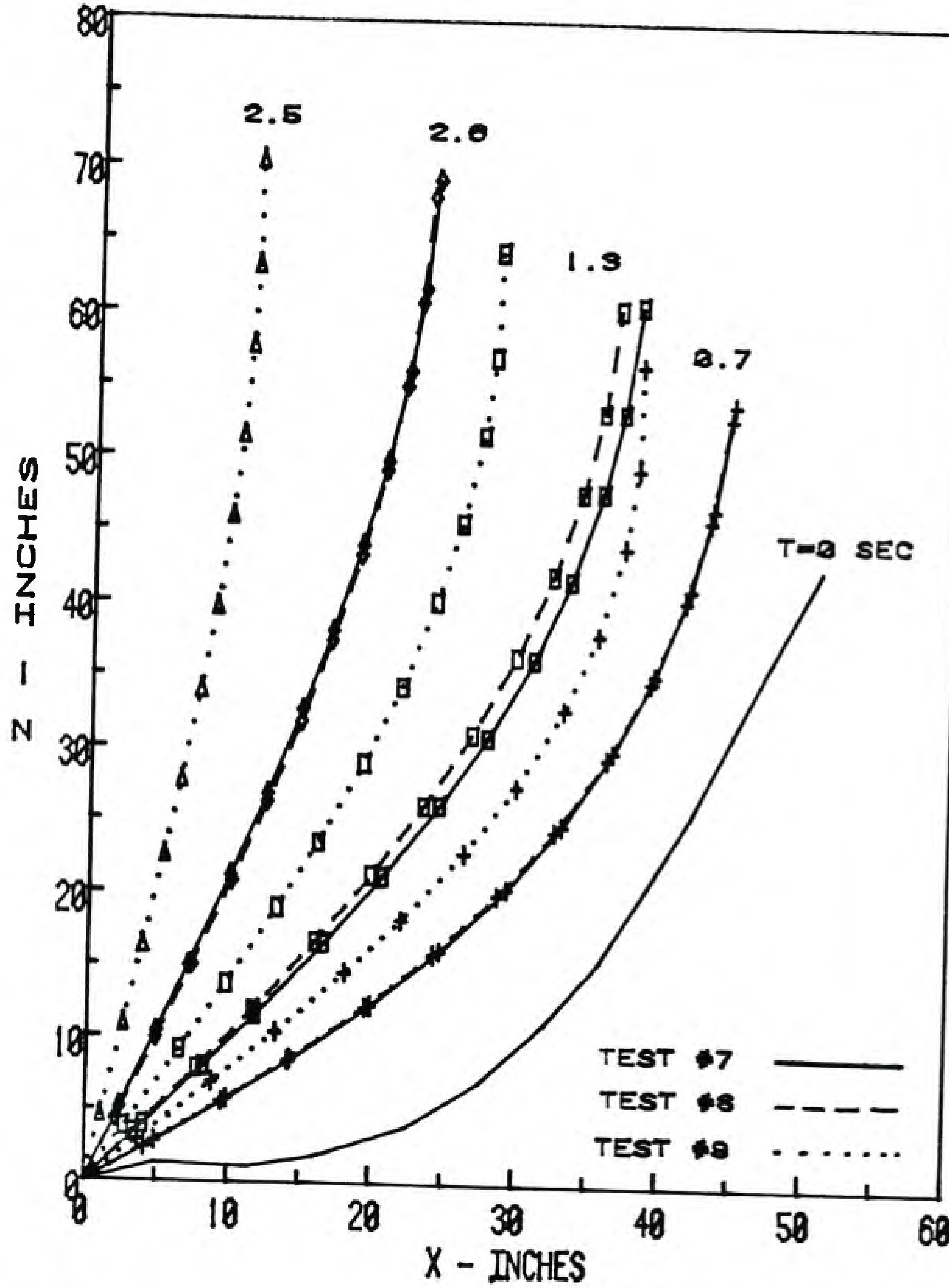

FIGURE 20. SEADYN DISPLACEMENT COMPARISON FOR TESTS #7, #8, AND #9.

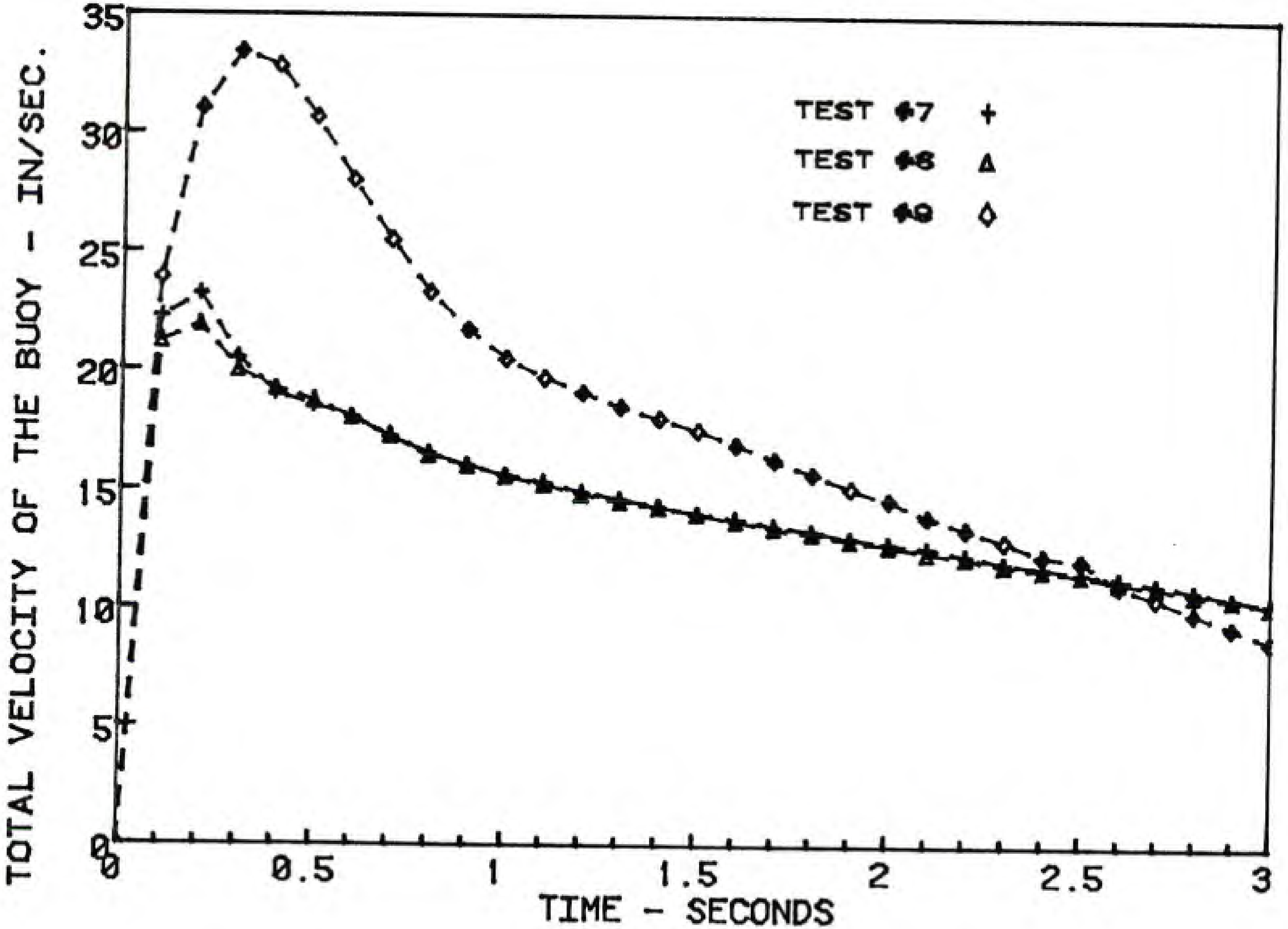

FIGURE 21. SEADYN BUOY VELOCITY COMPARISON FOR TESTS #7, #8, AND #9.

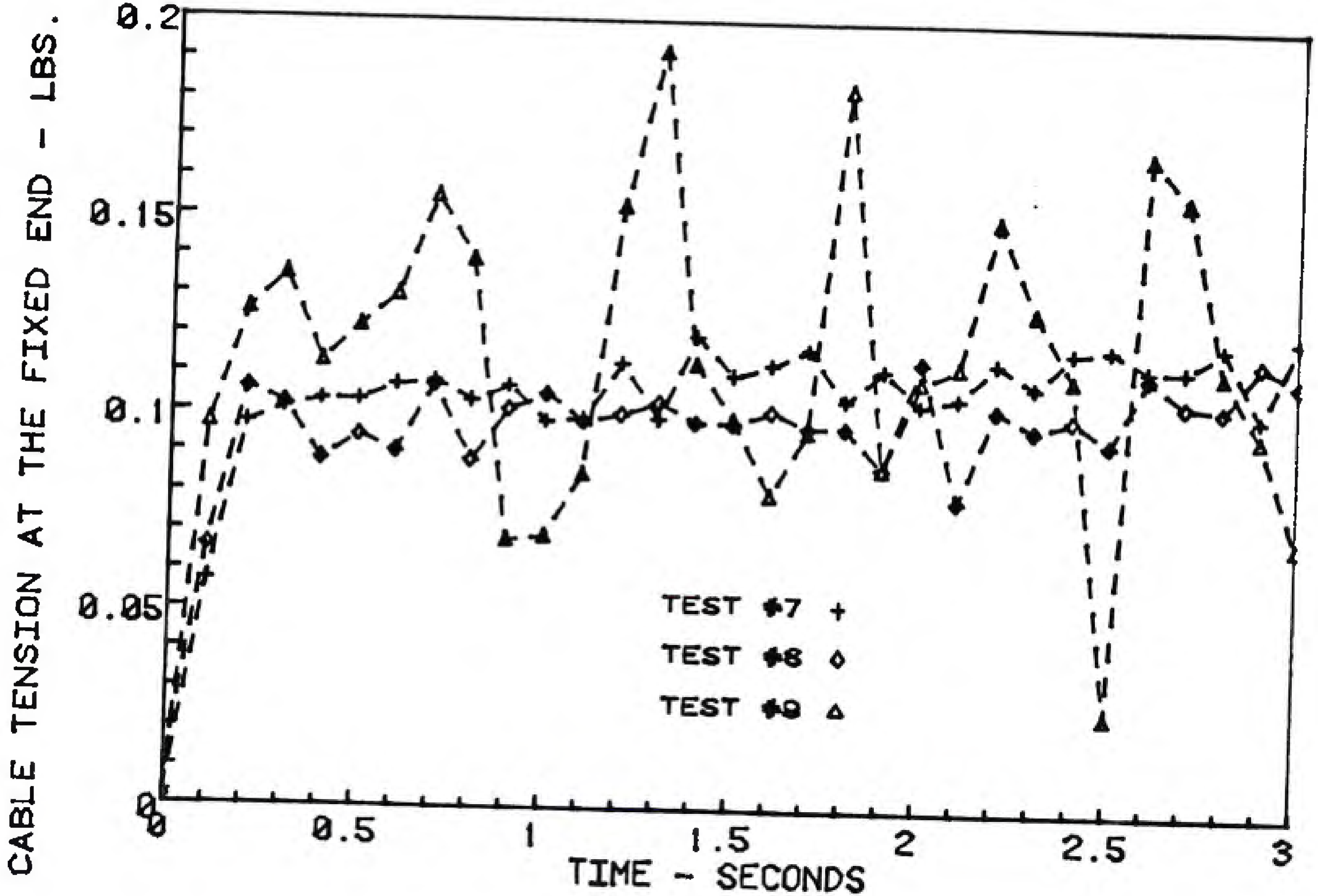

FIGURE 22. SEADYN TENSION COMPARISON FOR TESTS #7, #8, AND #9.

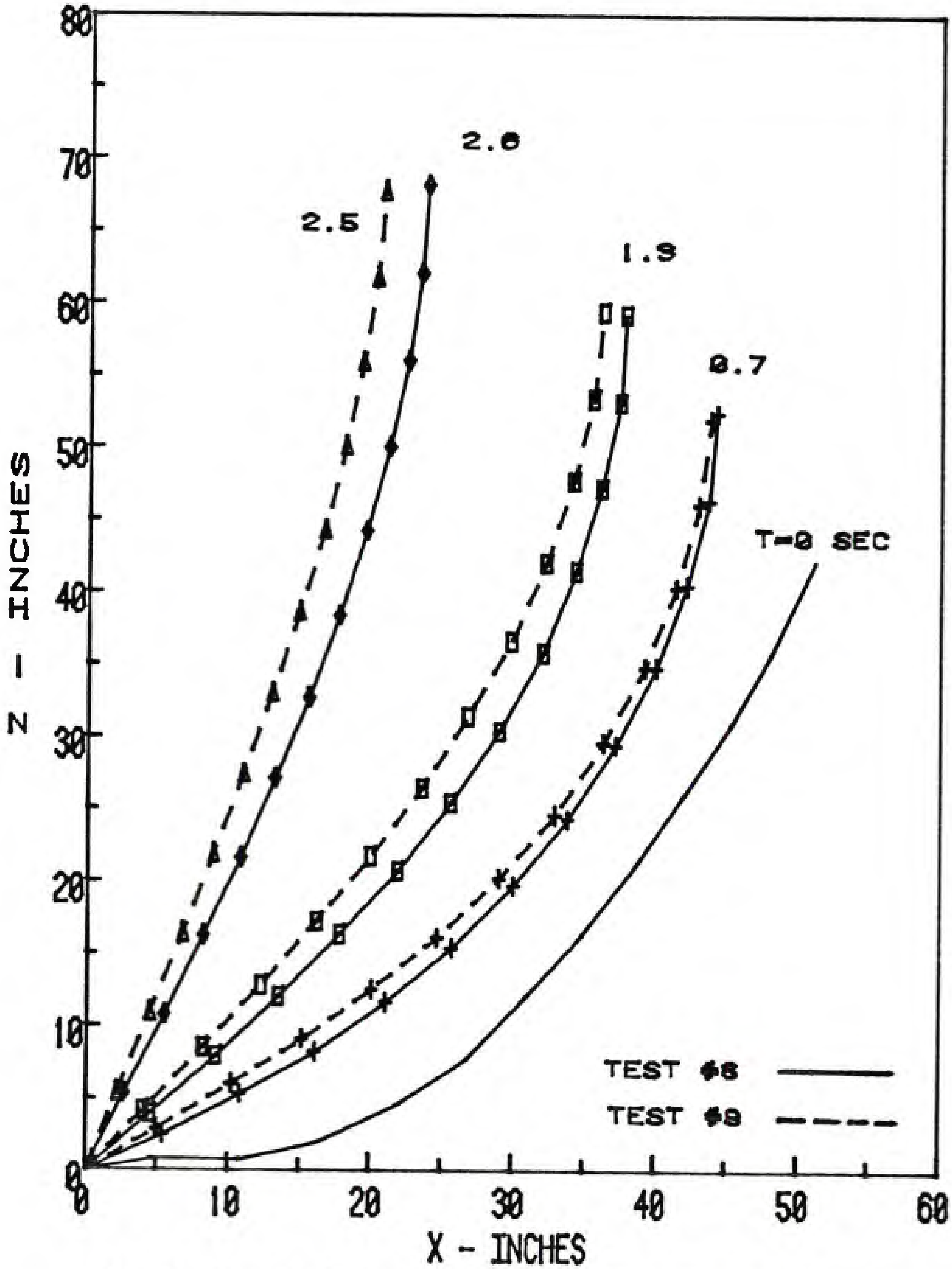

FIGURE 23. SNAPLG DISPLACEMENT COMPARISON FOR TESTS #8 AND #9.

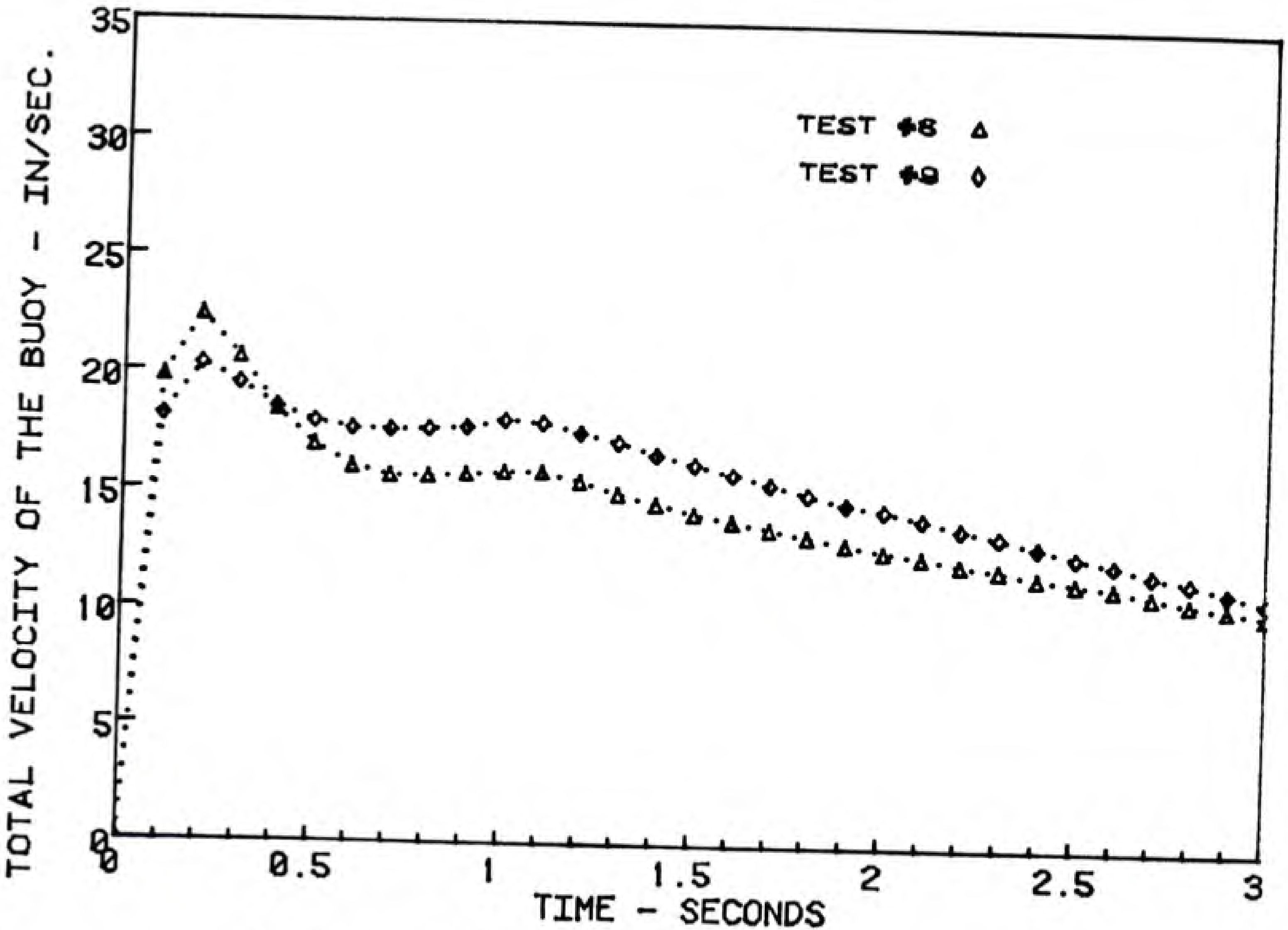

FIGURE 24. SNAPLG BUOY VELOCITY COMPARISON FOR TESTS #8 AND #9.

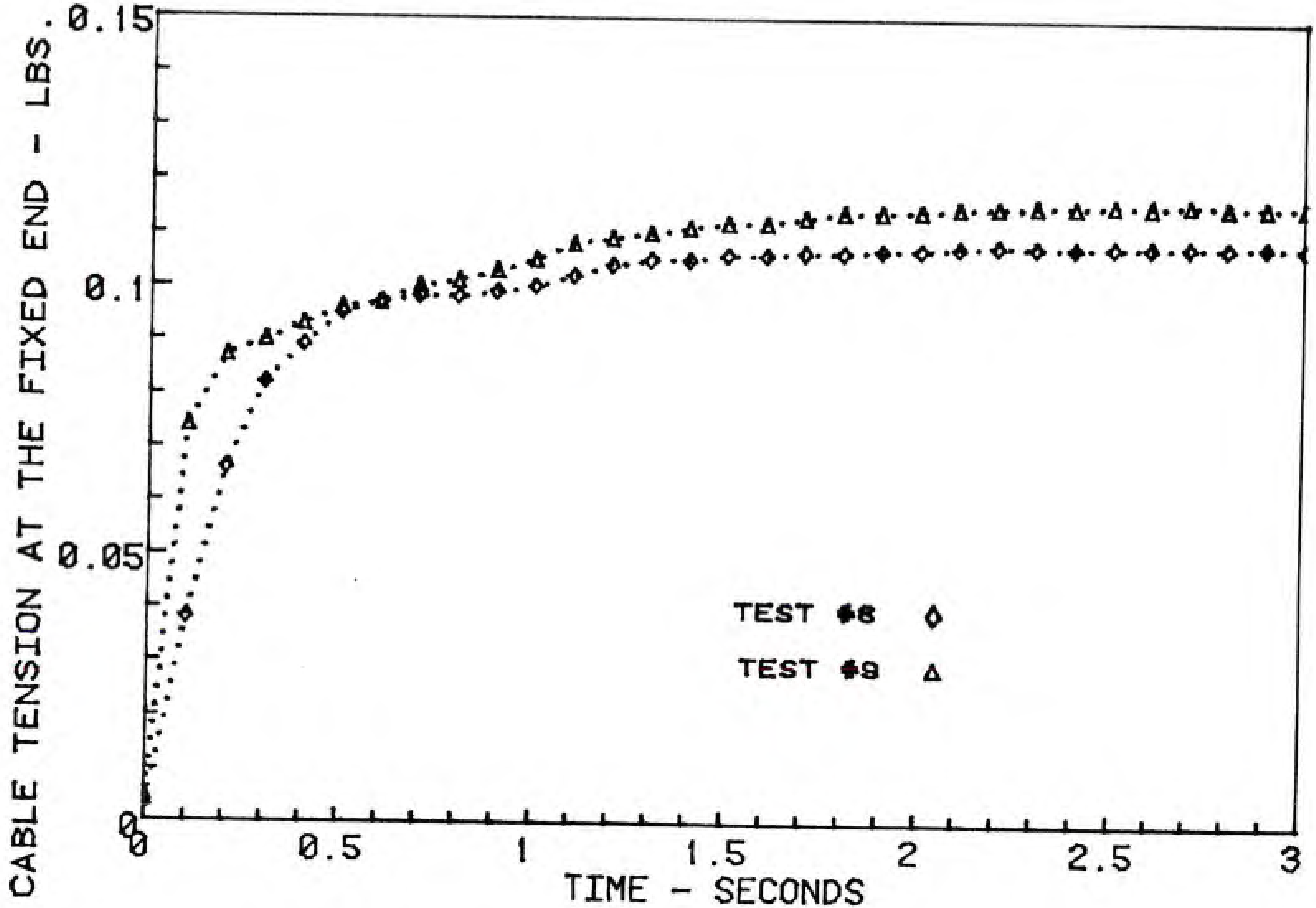

FIGURE 25. SNAPLG TENSION COMPARISON FOR TESTS #8 AND #9.

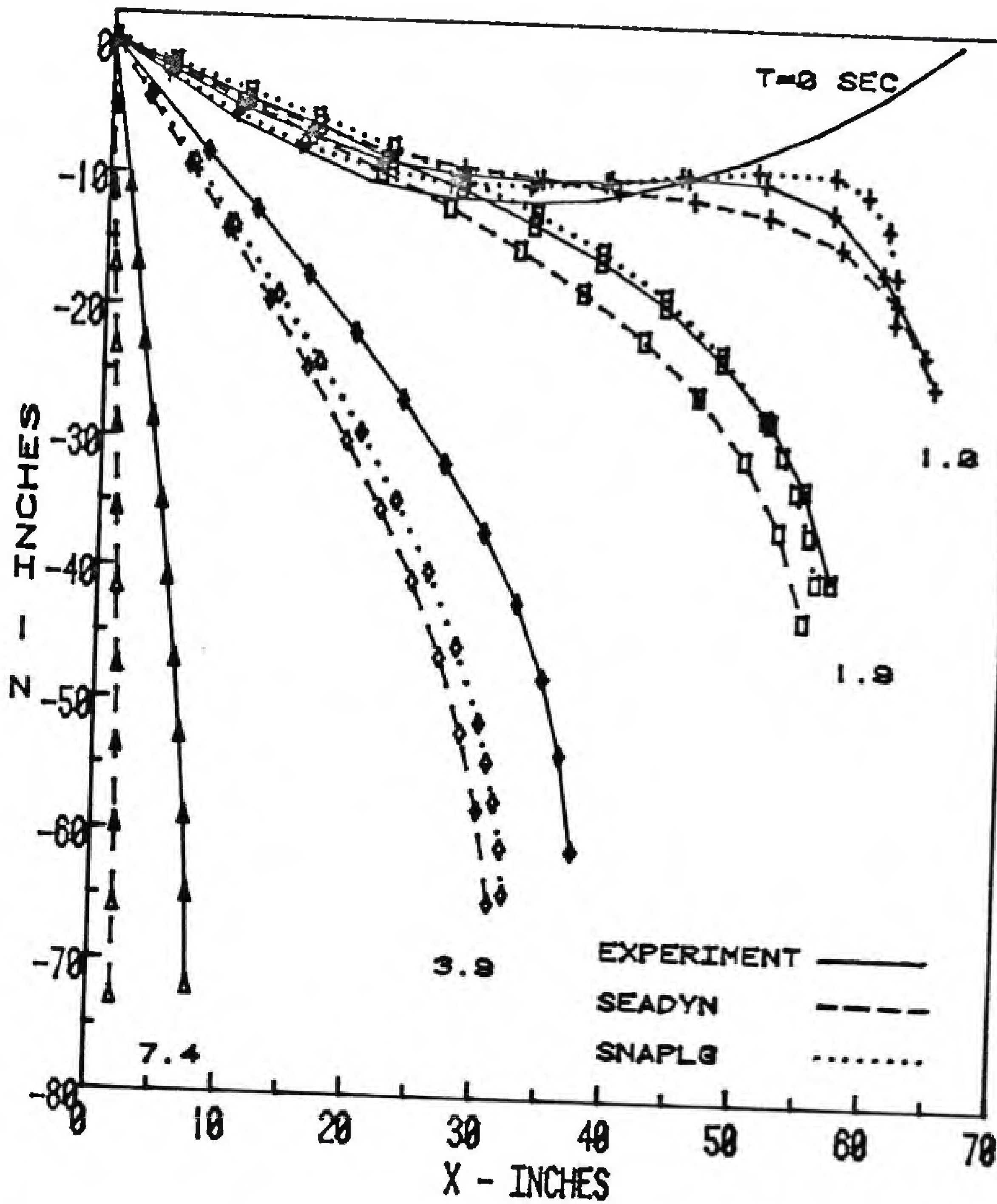

FIGURE 26. DISPLACEMENT COMPARISON FOR TEST #32.

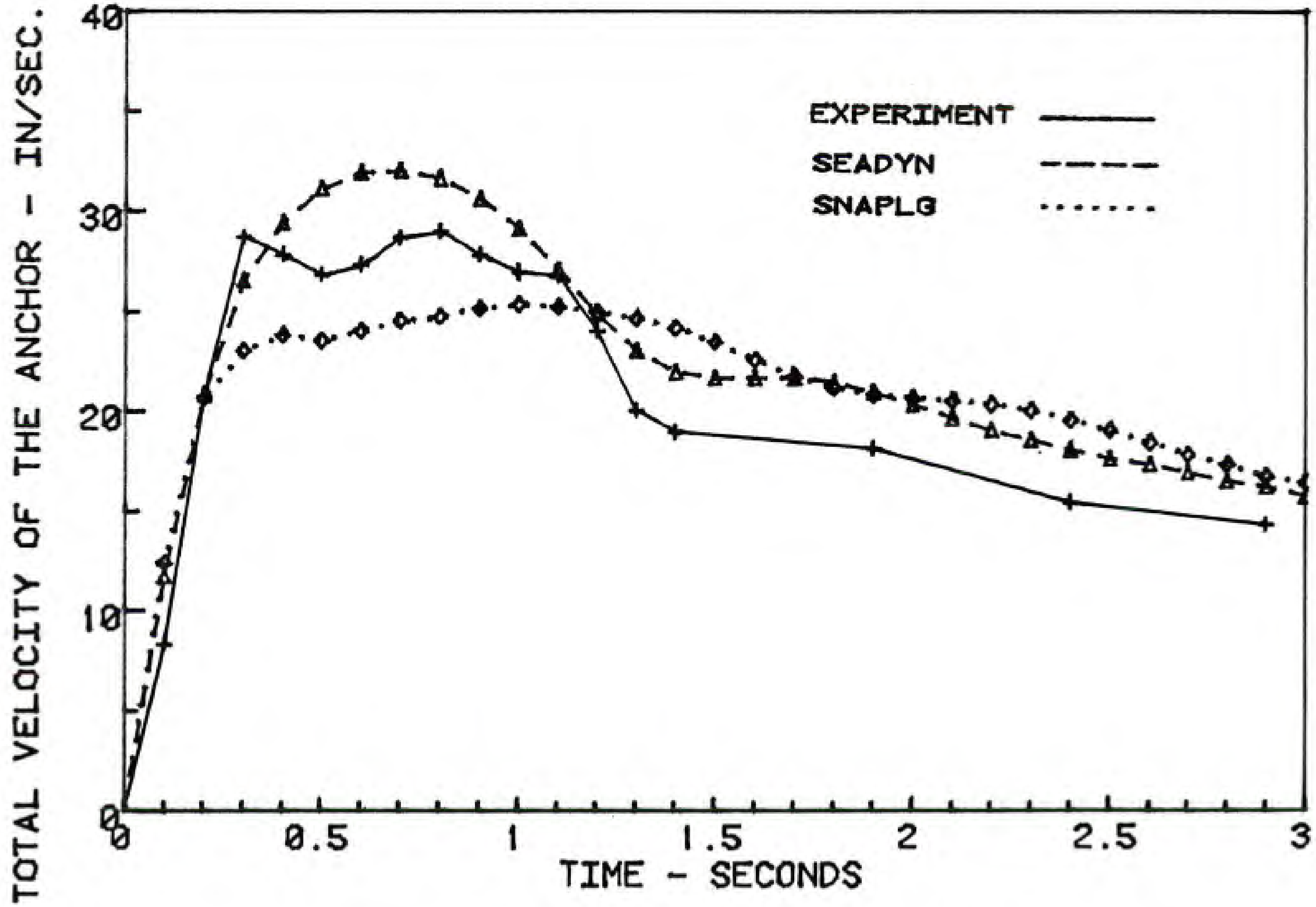

FIGURE 27. ANCHOR VELOCITY COMPARISON FOR TEST #32.

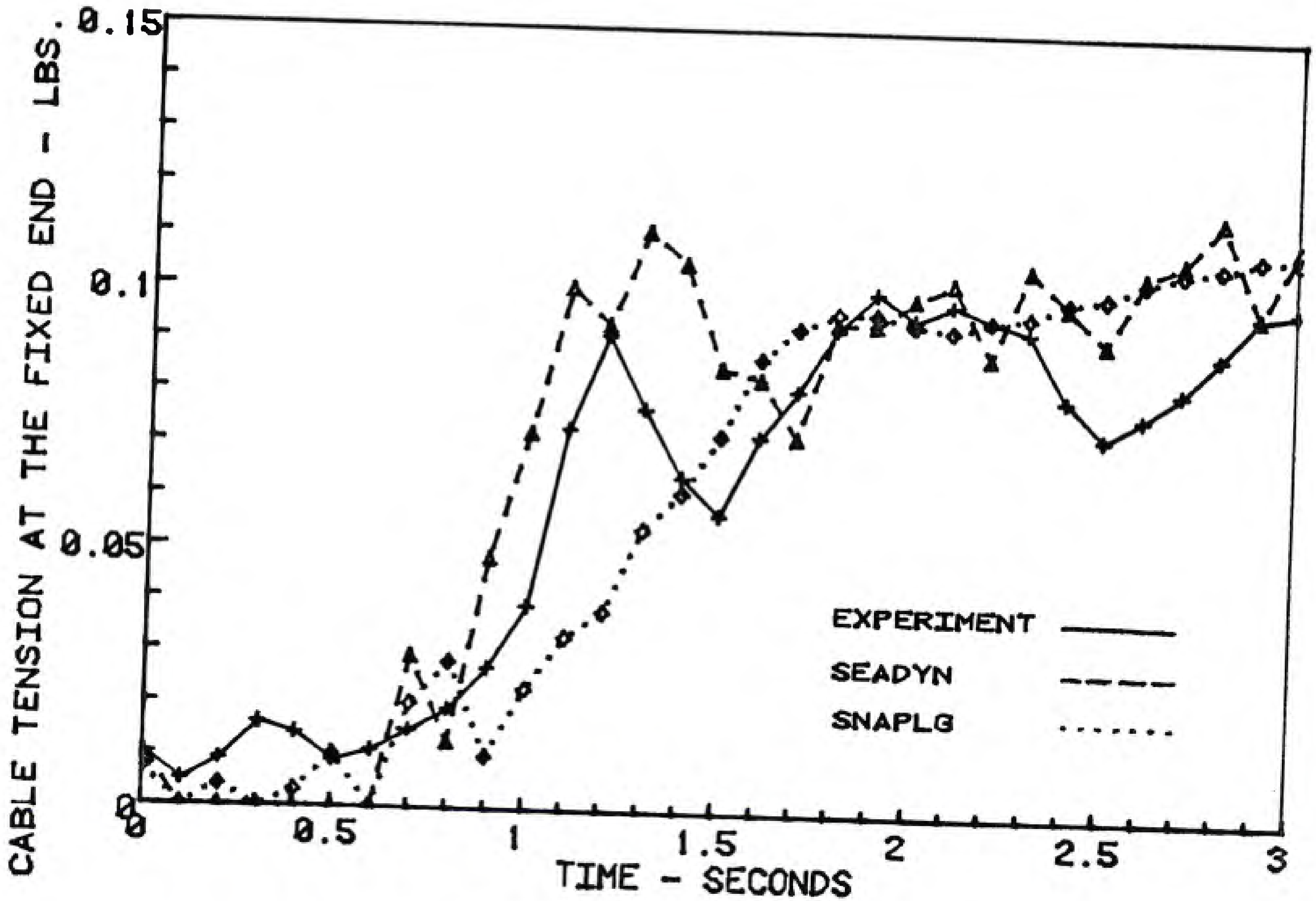

FIGURE 28. TENSION COMPARISON FOR TEST #32.

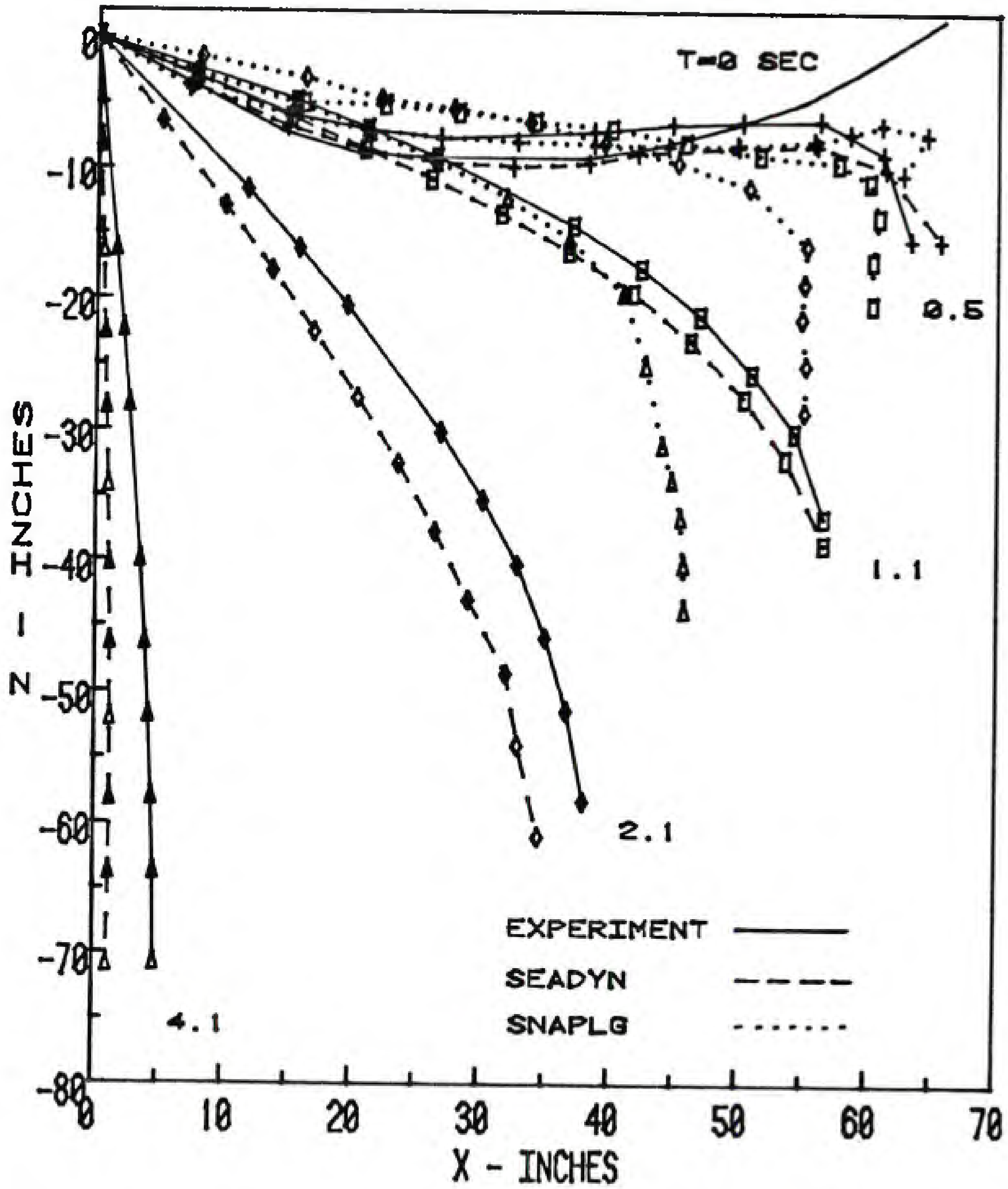

FIGURE 29. DISPLACEMENT COMPARISON FOR TEST #35.

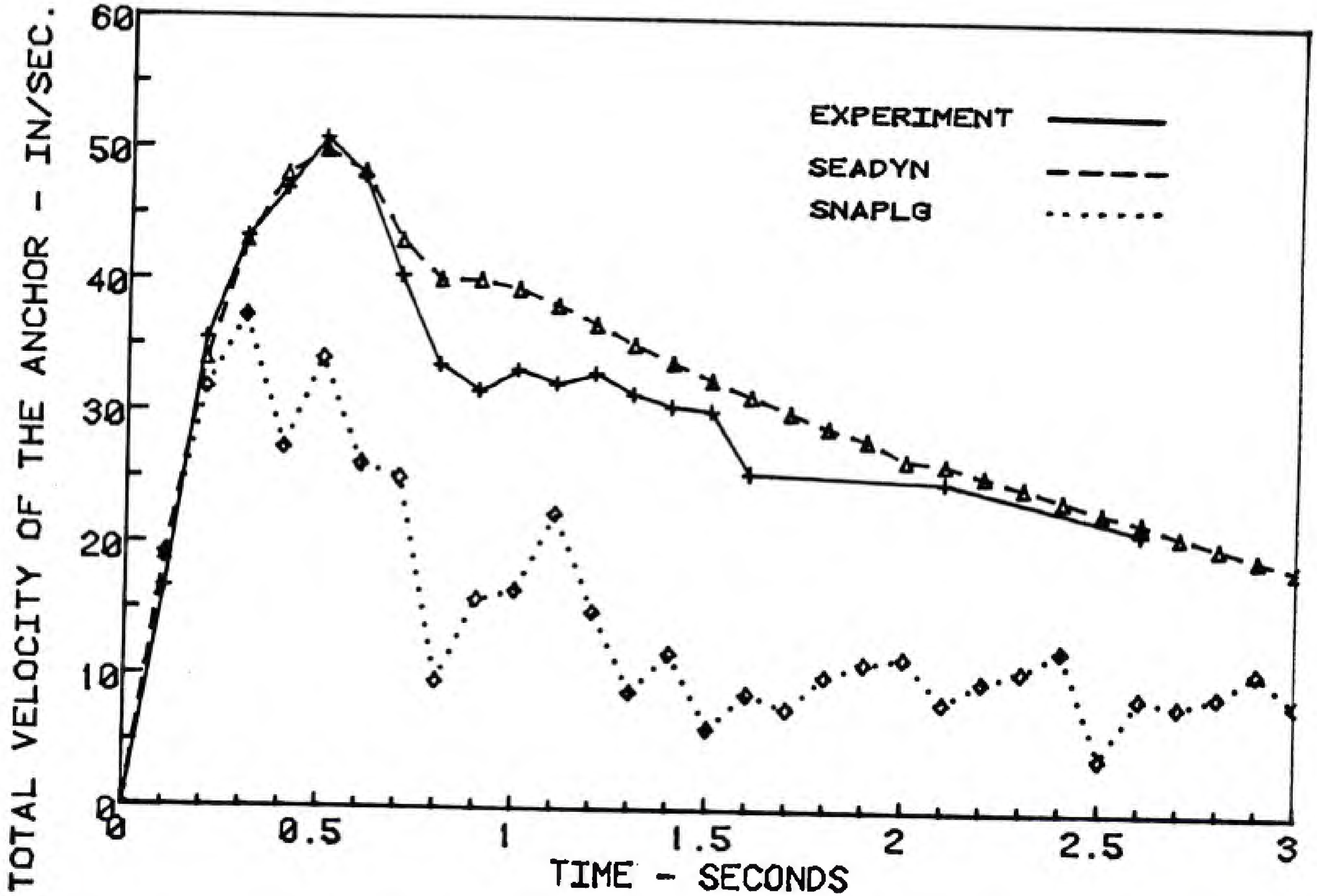

FIGURE 30. ANCHOR VELOCITY COMPARISON FOR TEST #35.

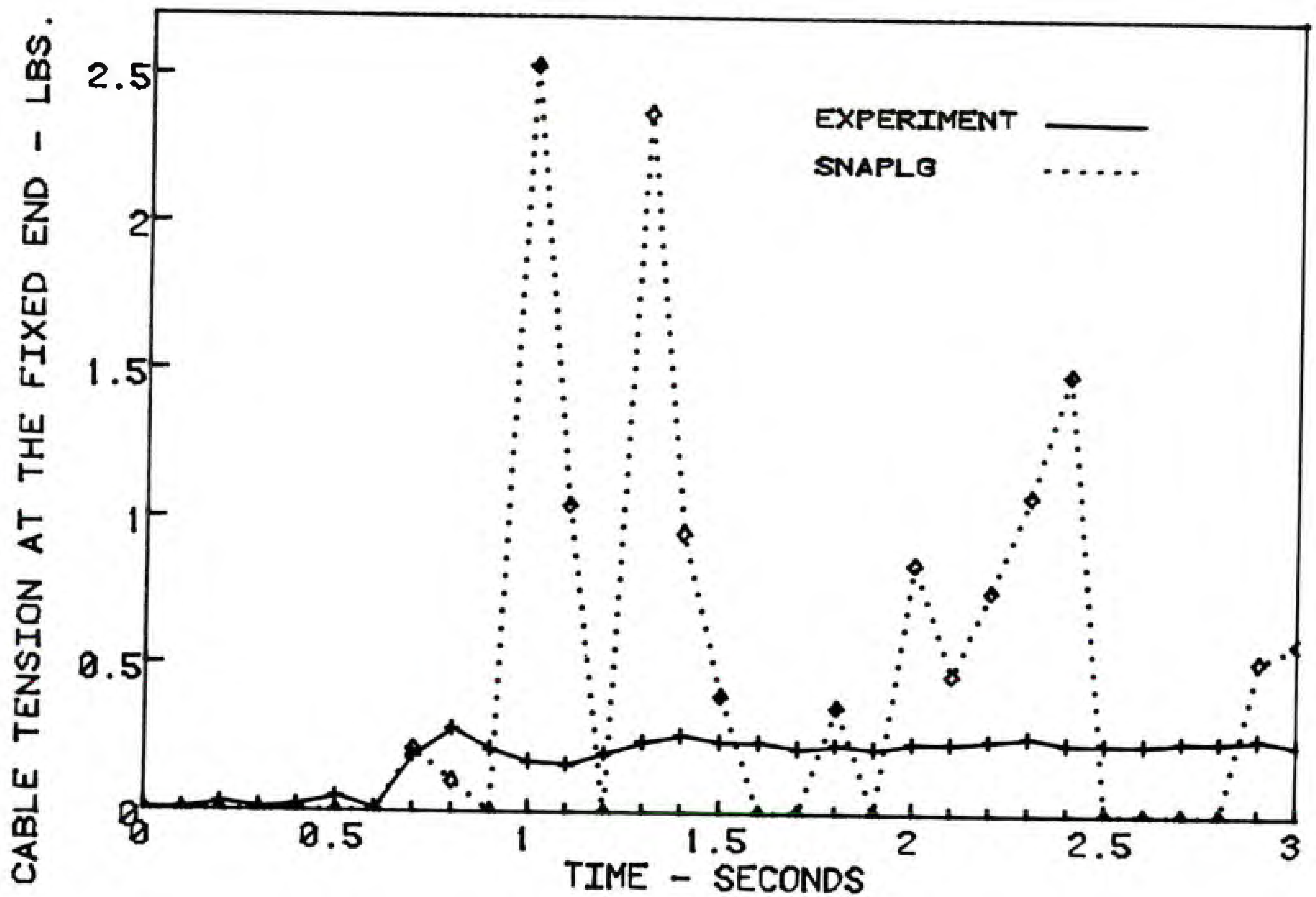

FIGURE 31-a. TENSION COMPARISON FOR TEST #35.

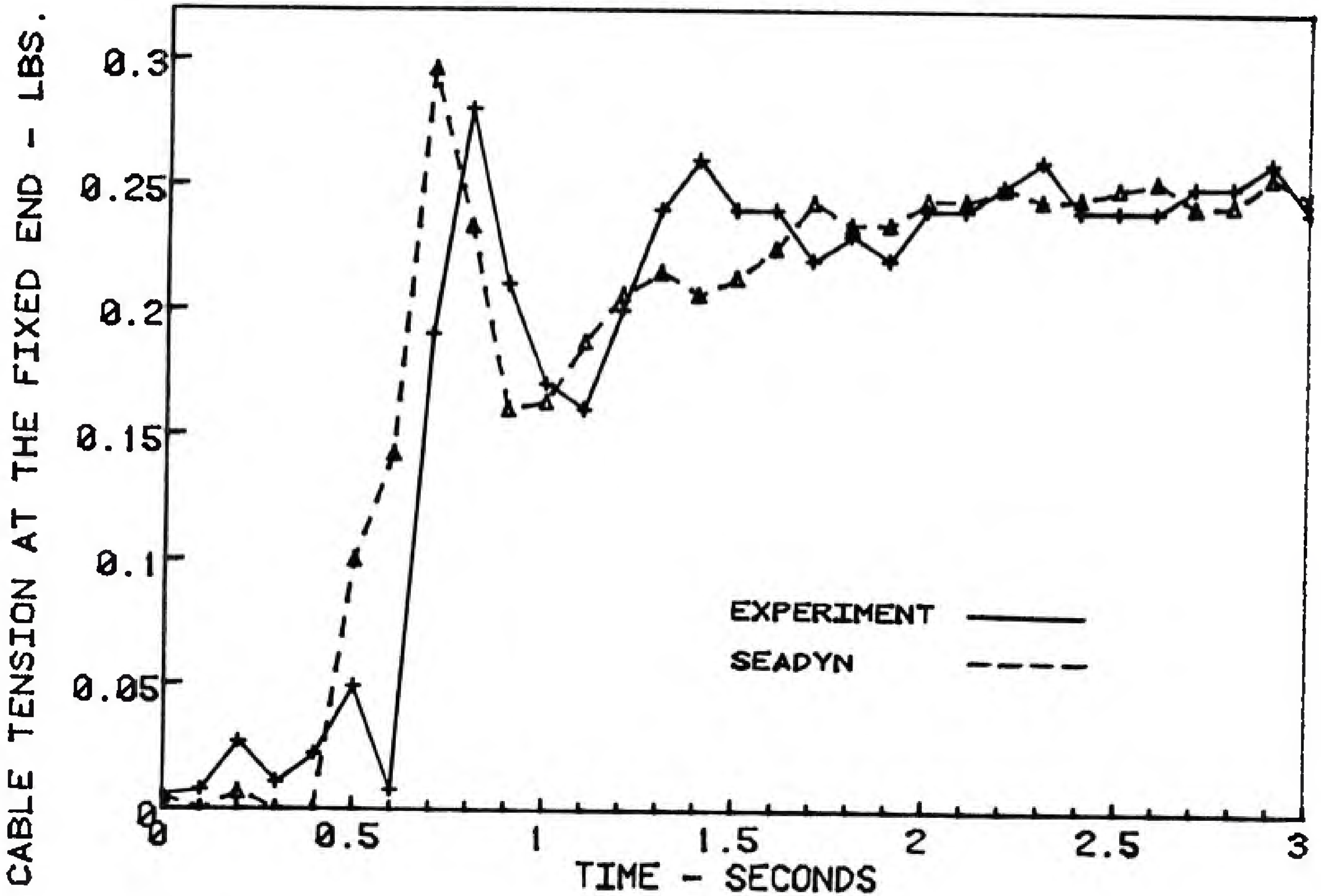

FIGURE 31-b. TENSION COMPARISON FOR TEST #35.

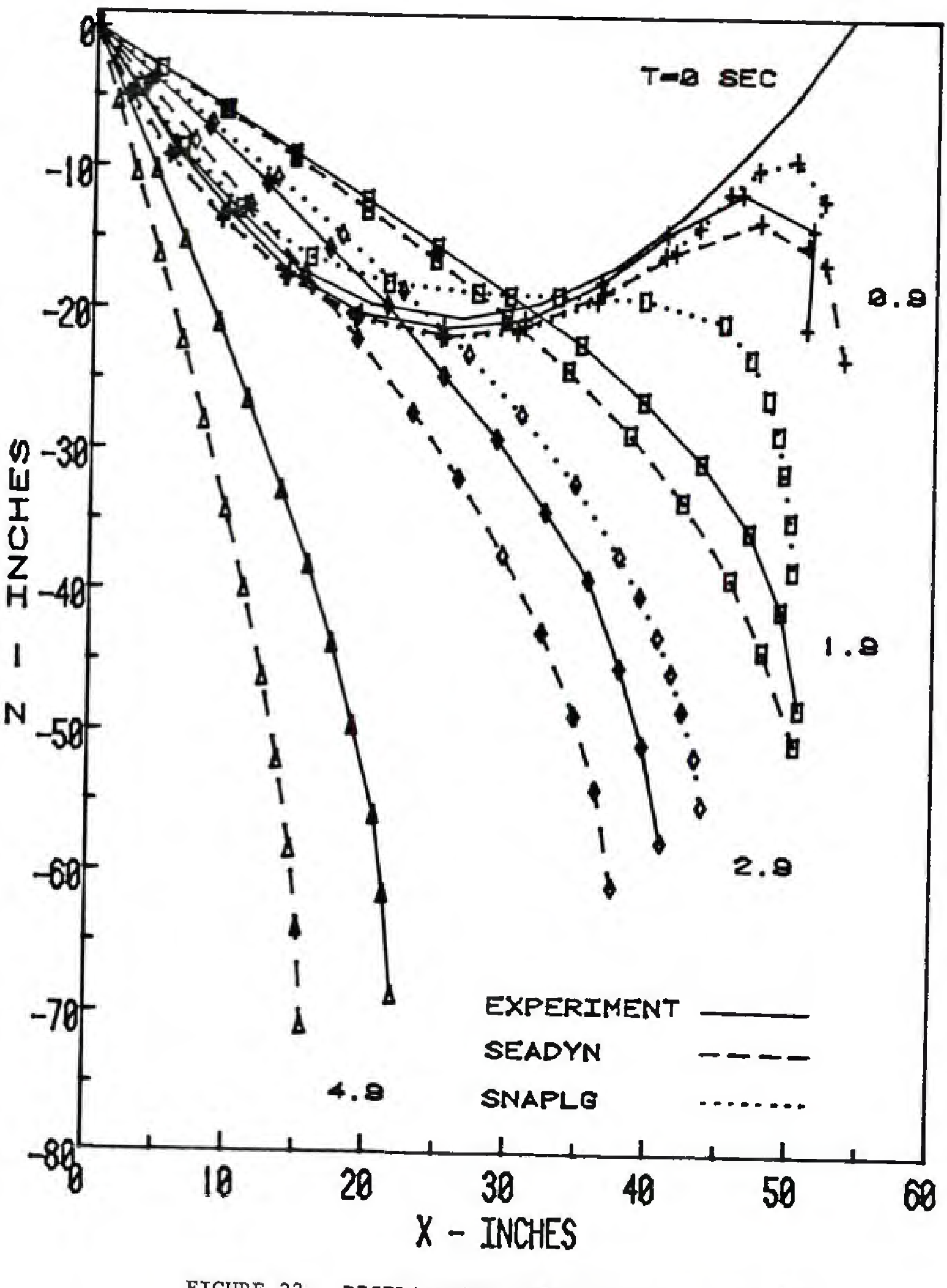

FIGURE 32. DISPLACEMENT COMPARISON FOR TEST #39.

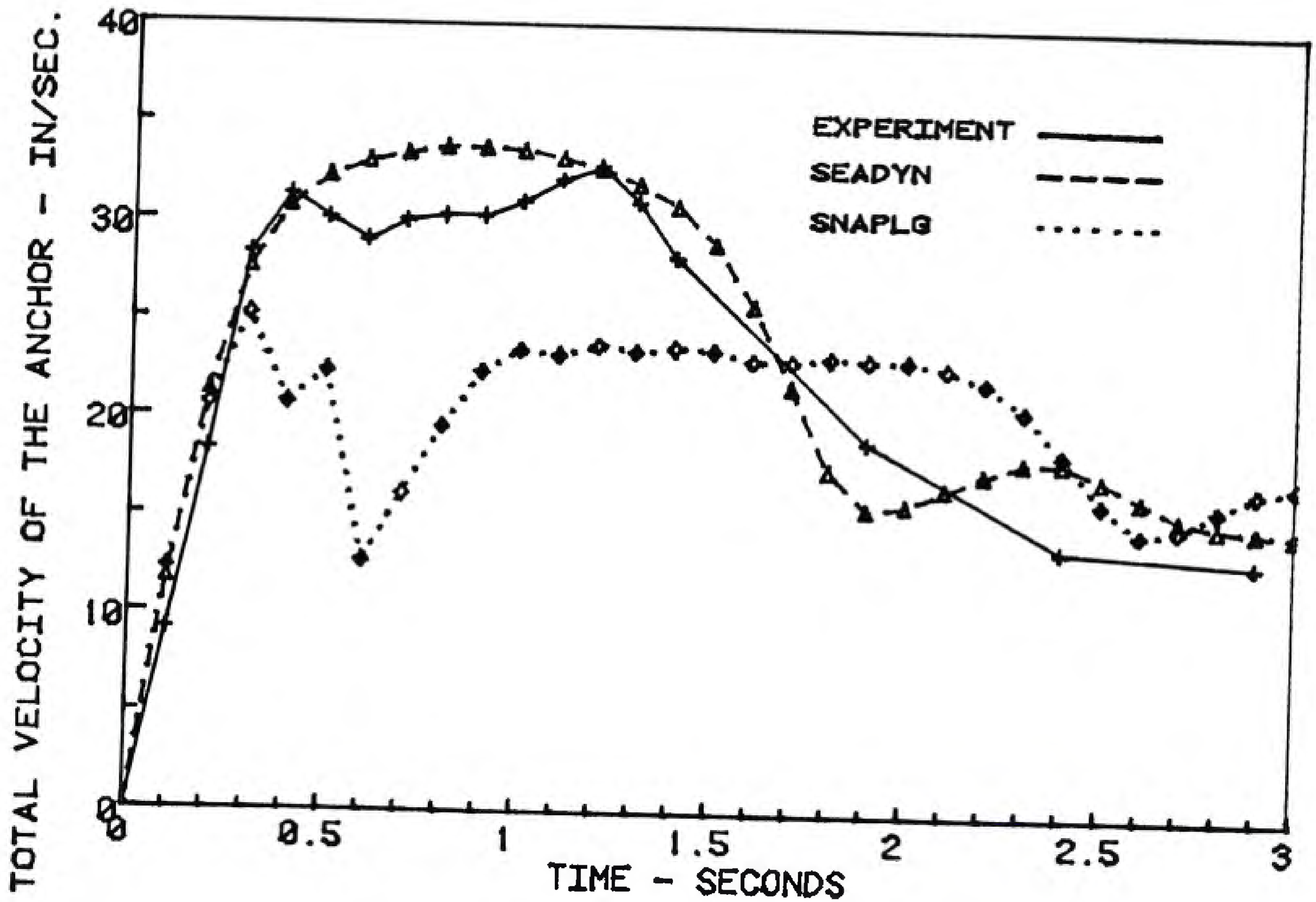

FIGURE 33. ANCHOR VELOCITY COMPARISON FOR TEST #39.

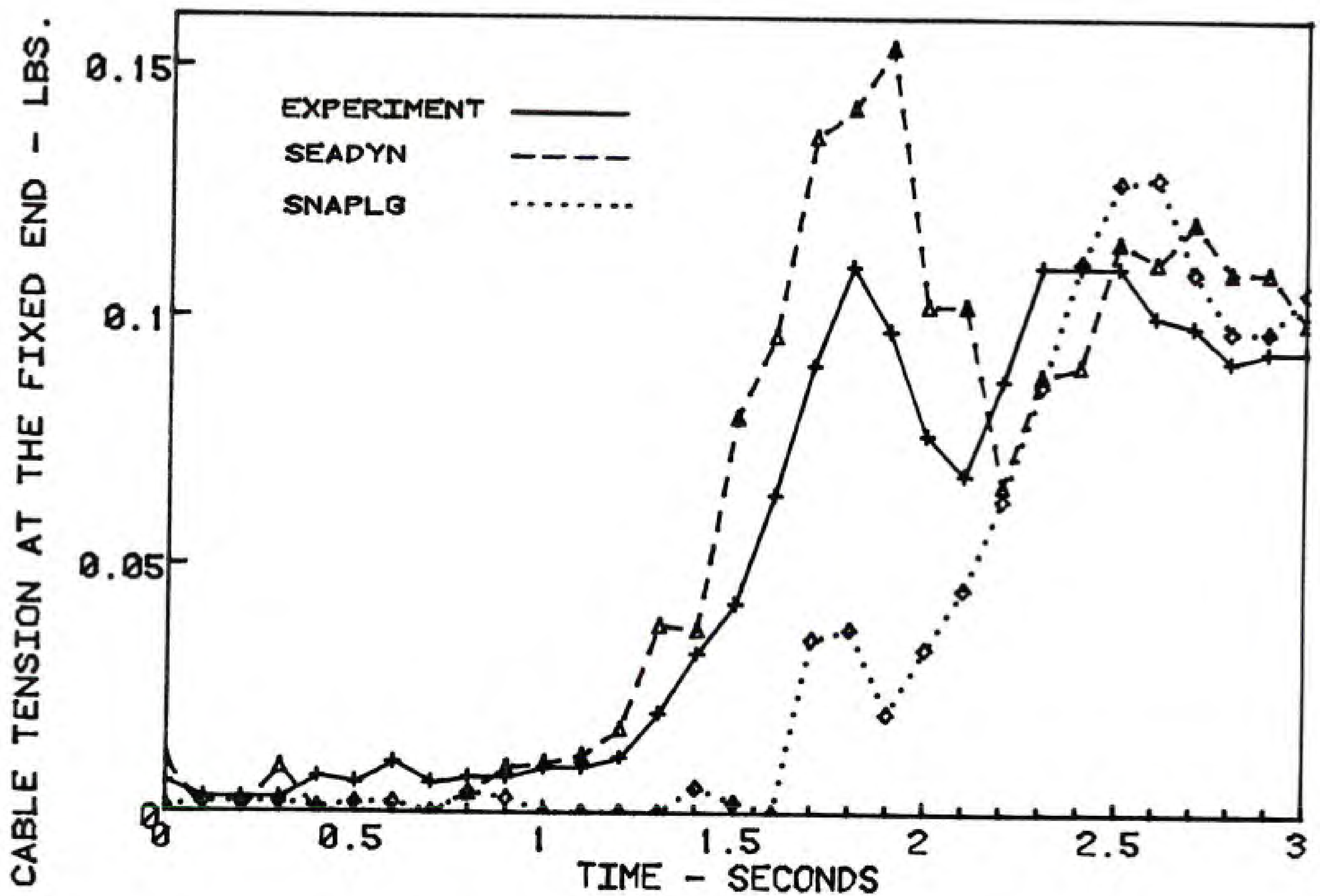

FIGURE 34. TENSION COMPARISON FOR TEST #39.

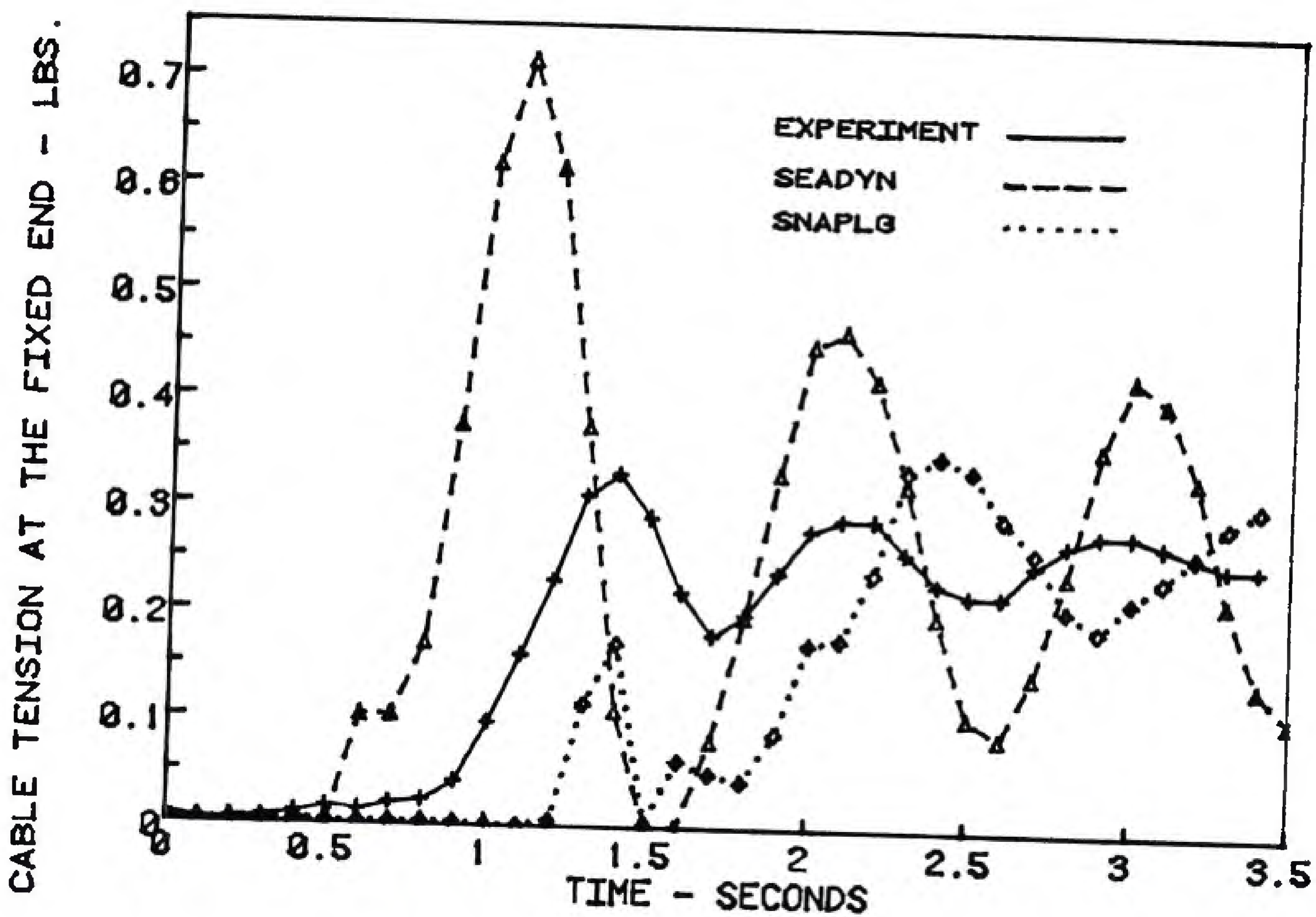

FIGURE 35. TENSION COMPARISON FOR TEST #43.

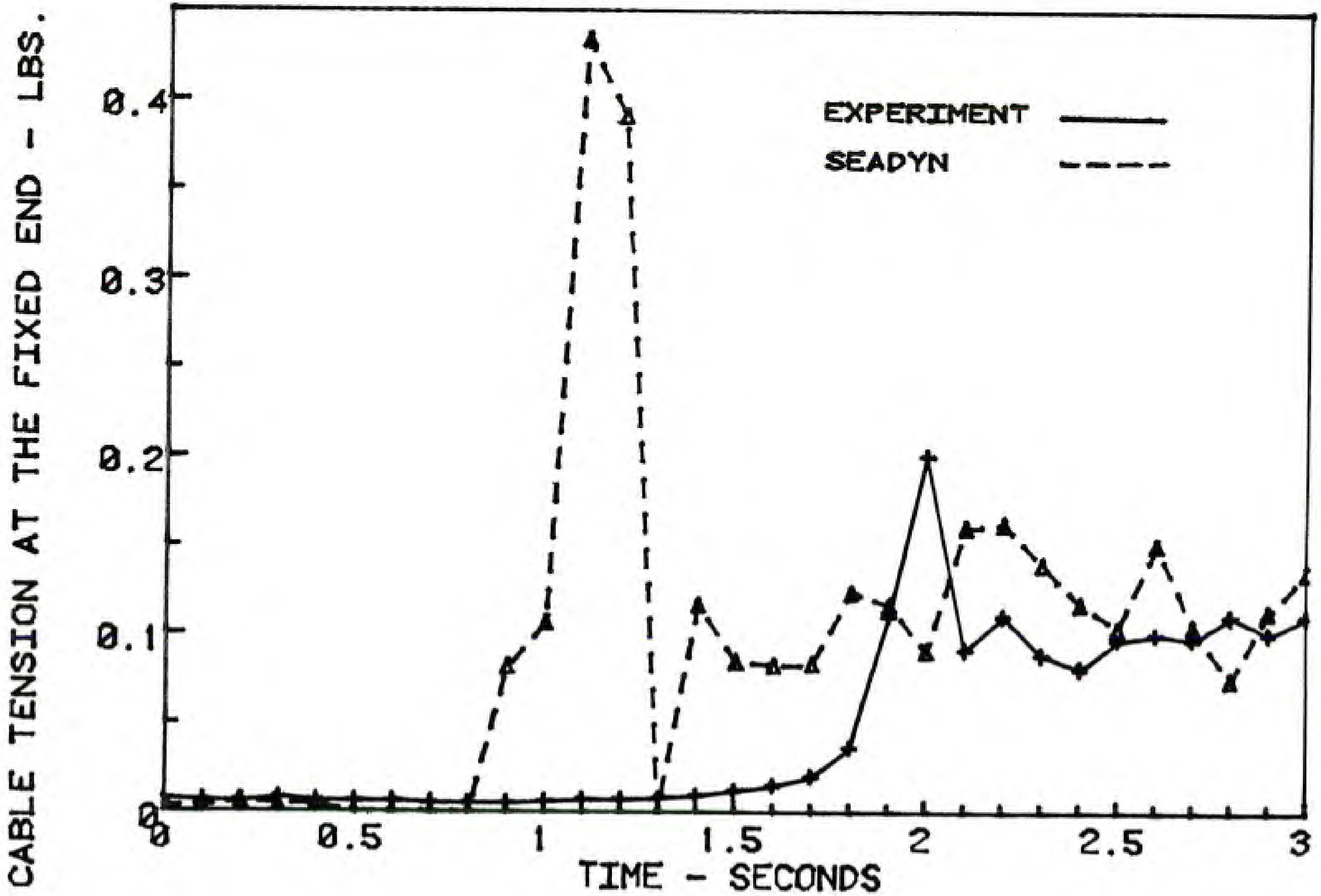

FIGURE 36. TENSION COMPARISON FOR TEST #46.

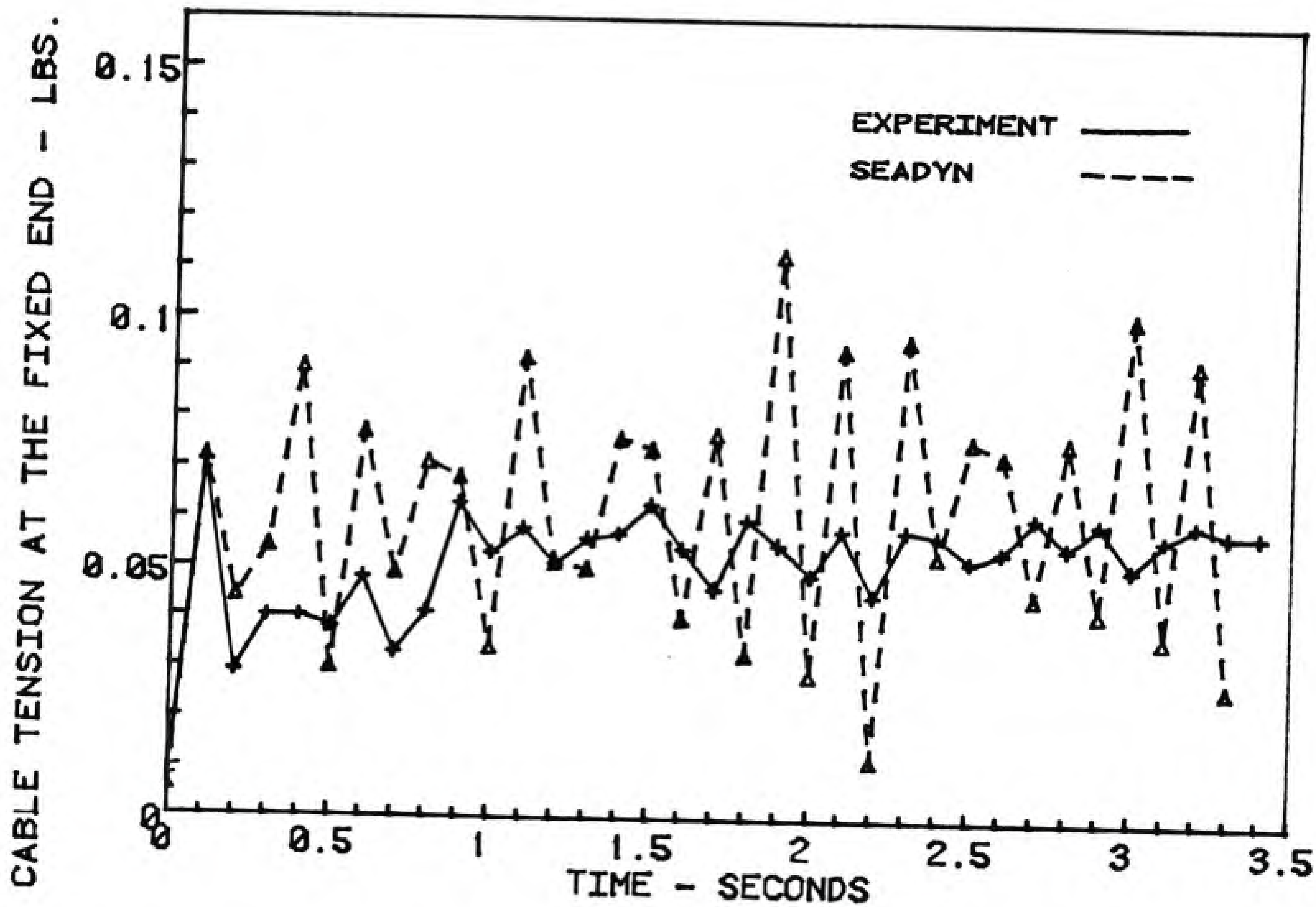

FIGURE 37. TENSION COMPARISON FOR TEST #60.

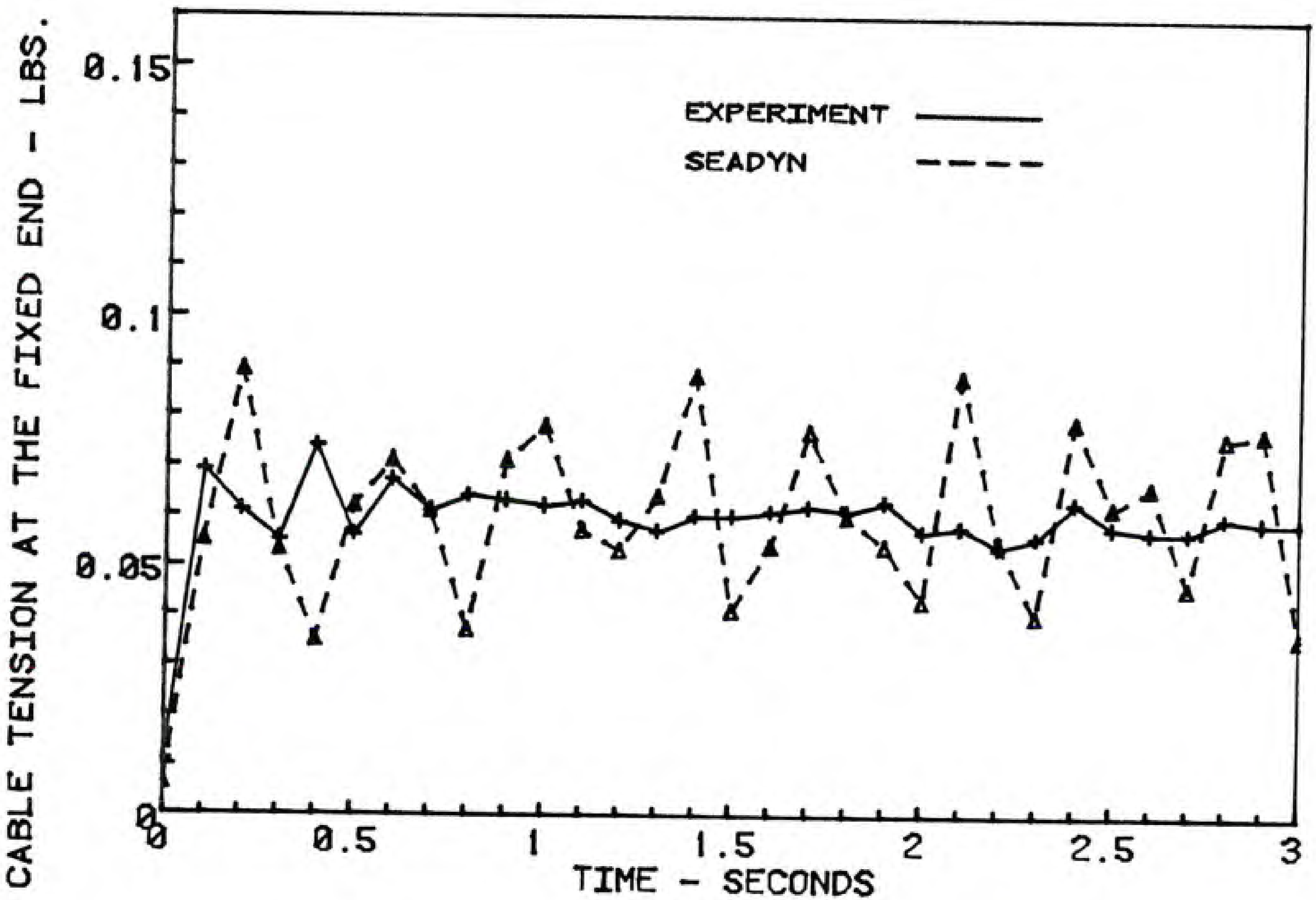

FIGURE 38. TENSION COMPARISON FOR TEST #61.

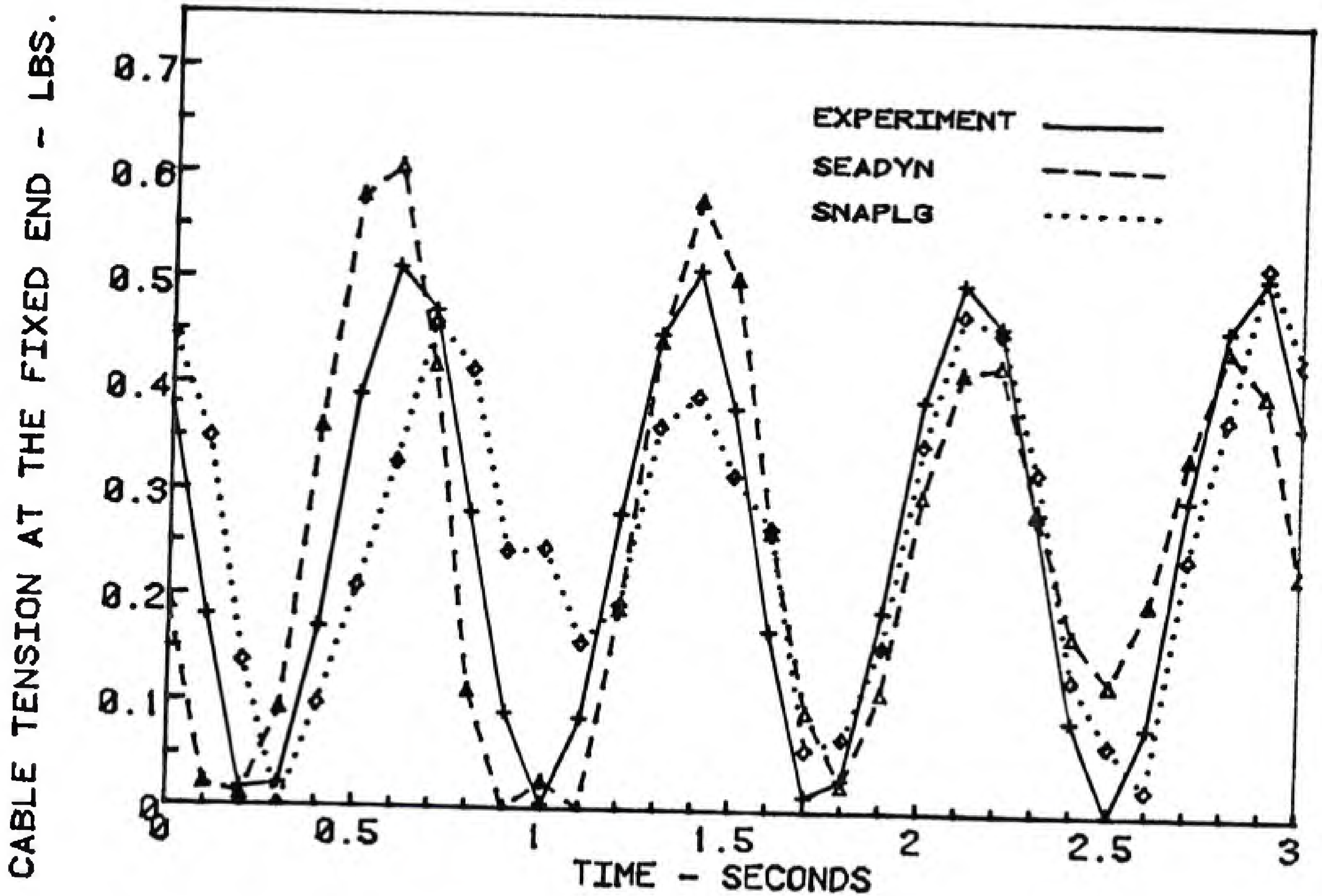

FIGURE 39. TENSION COMPARISON FOR TEST #67.

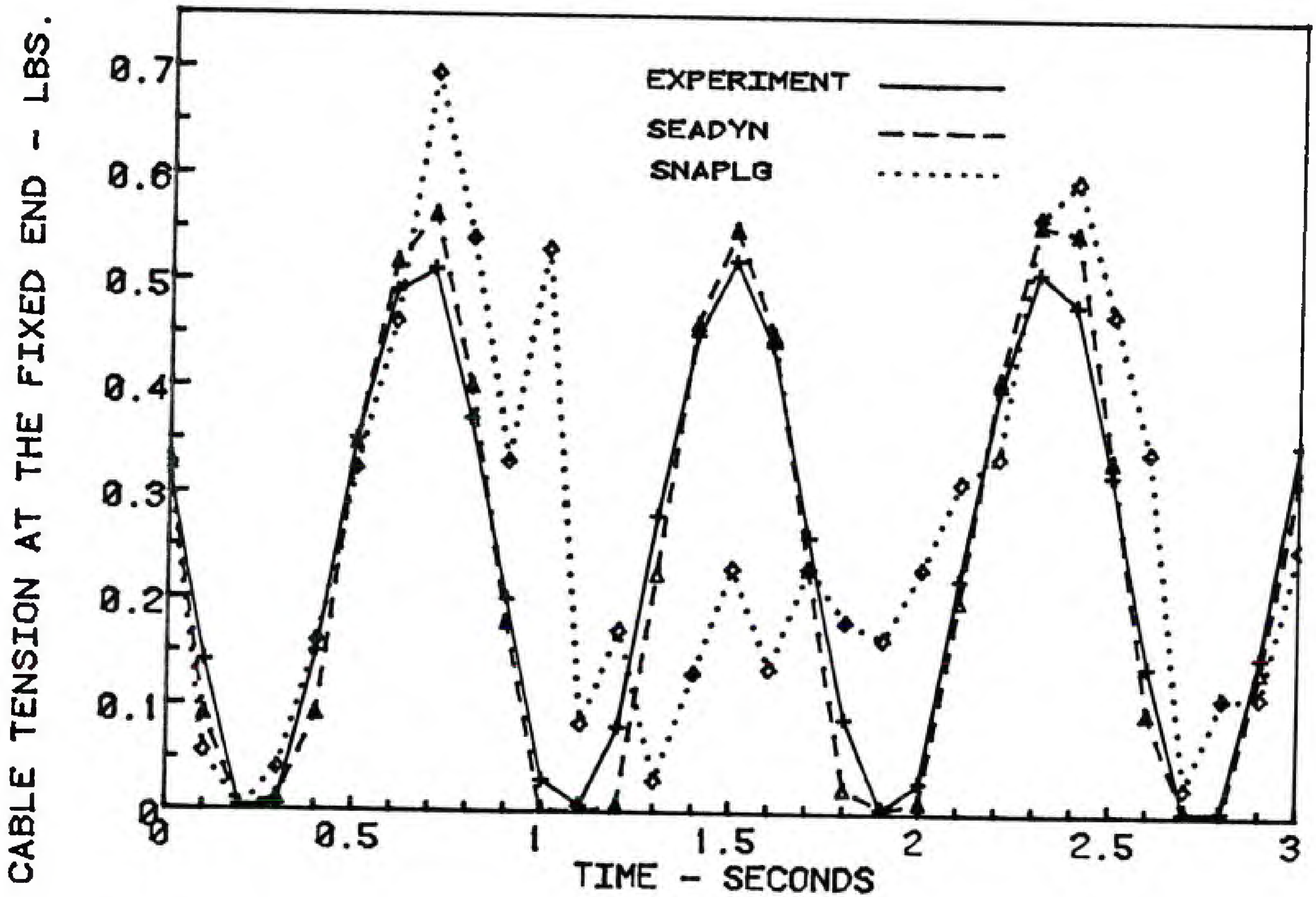

FIGURE 40. TENSION COMPARISON FOR TEST #68.

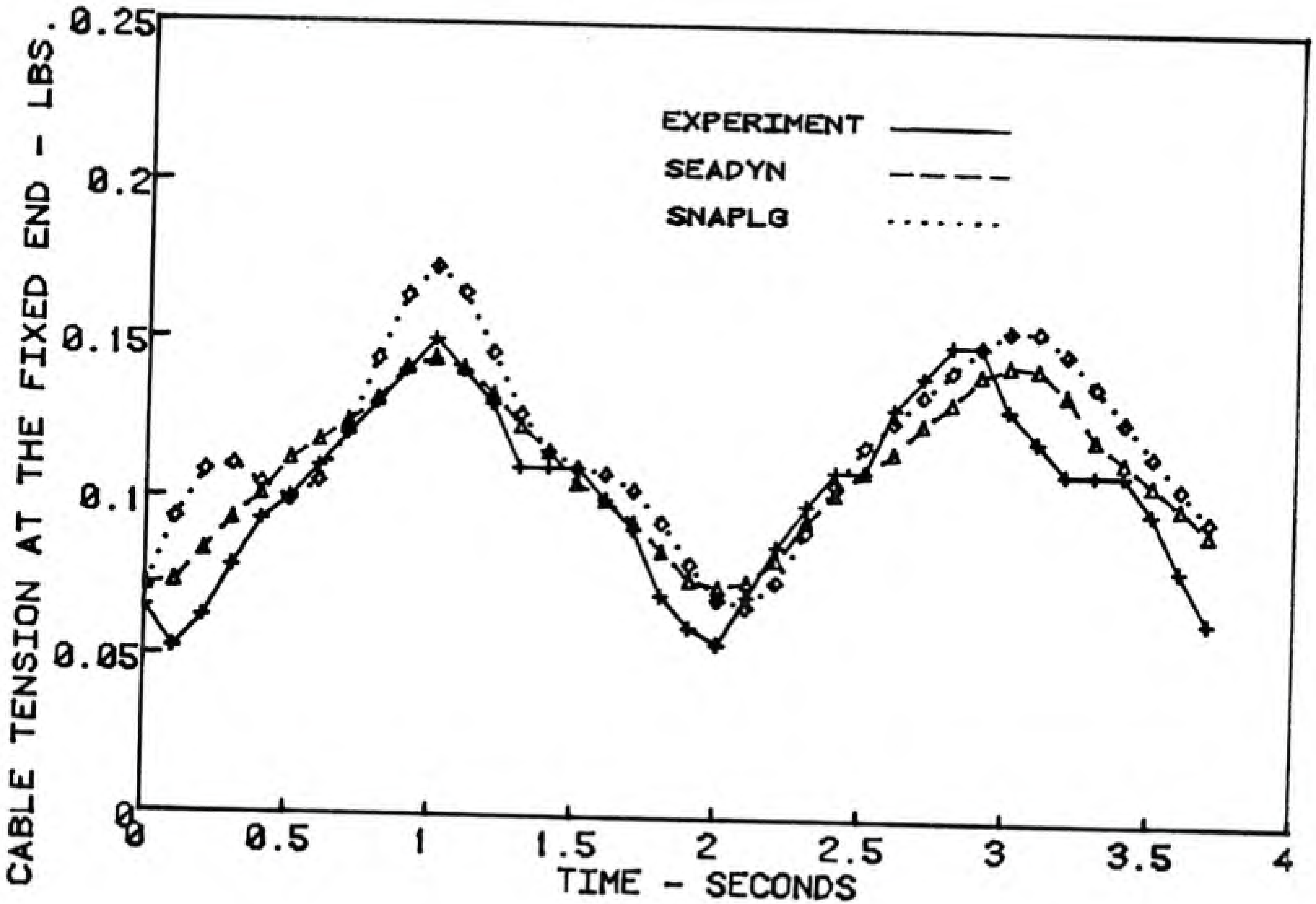

FIGURE 41. TENSION COMPARISON FOR TEST #94.

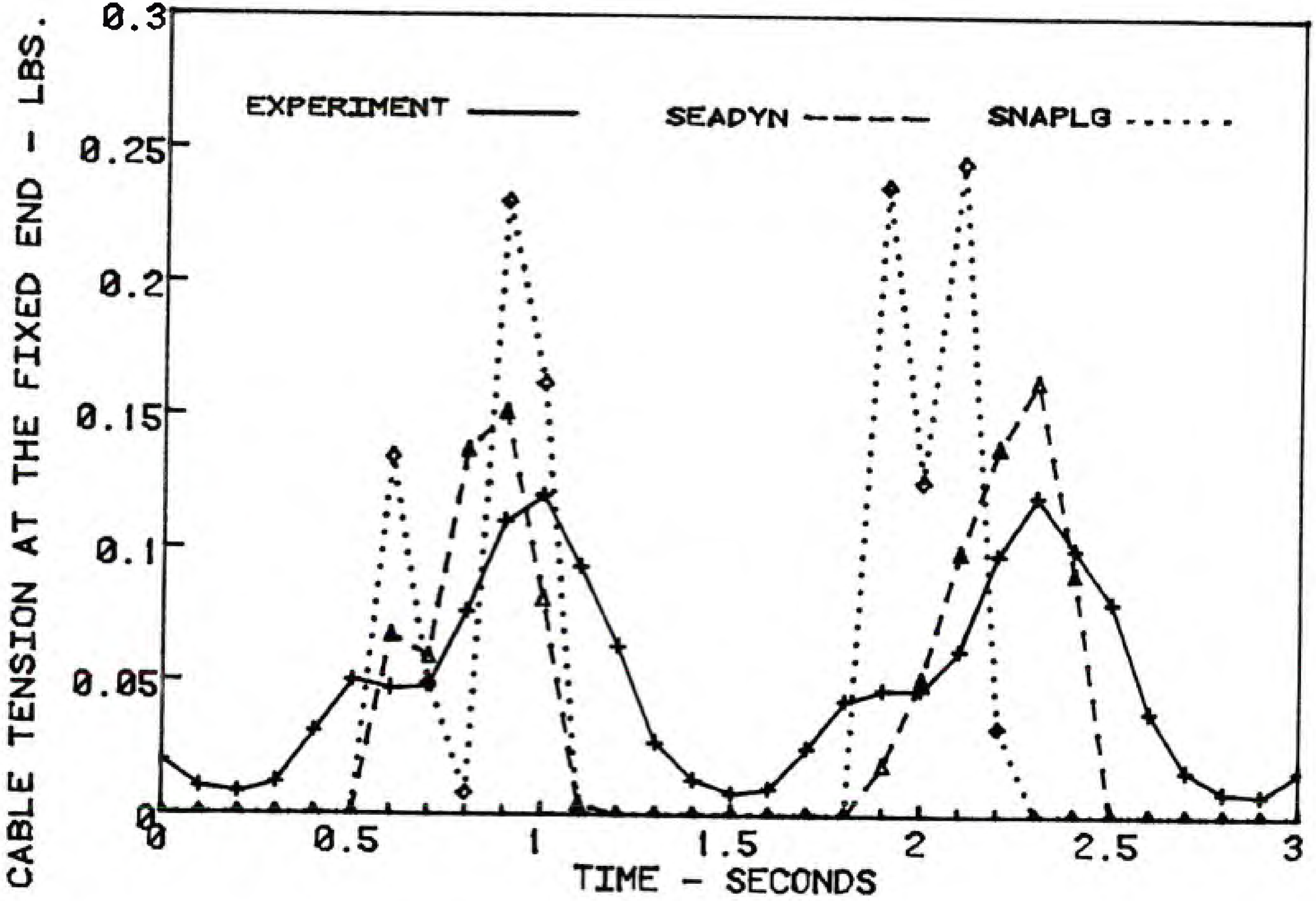

FIGURE 42. TENSION COMPARISON FOR TEST #133.

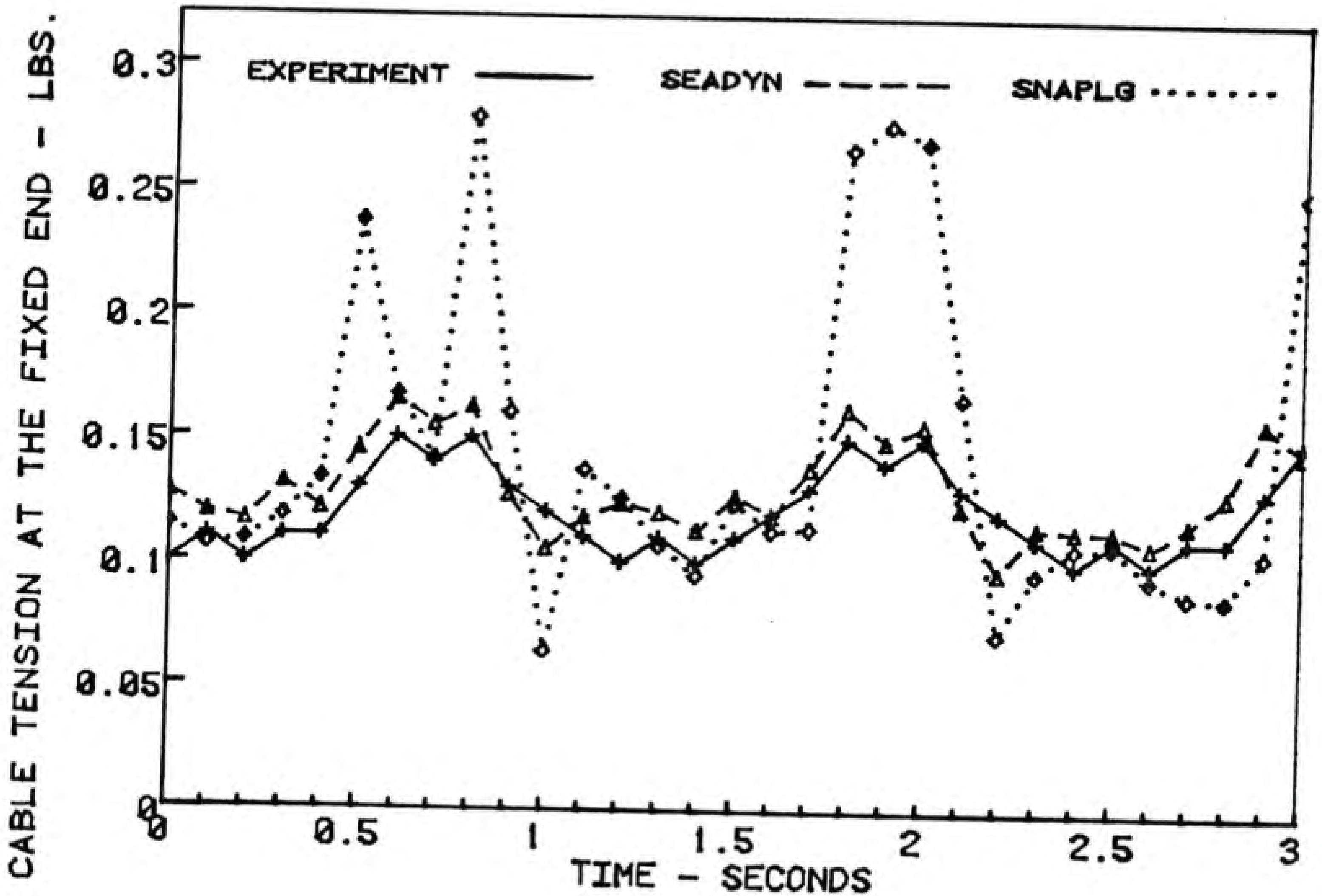

FIGURE 43. TENSION COMPARISON FOR TEST #142.