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16. Abstract

During the construction of the I-295 cable-stayed bridge, a number of the stays on the main span cantilever were instrumented with electrical resistance strain gages mounted directly on the wires of the seven-wire strands making up the stay cables. Measurements were taken beginning before tensioning and continuing until completion of the cantilever. Expected changes in the strains caused by lifting of segments and subsequent stay tensioning activities were observed. During the multi-strand tensioning activities on the instrumented stays, significant variability in the strain behavior of the individual strands was observed, a fact that should be considered in the design of cable-stay systems and tensioning methods.

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FIELD INSTRUMENTATION AND MEASURED RESPONSE OF THE I-295 CABLE-STAYED BRIDGE

INTERIM REPORT ON CONSTRUCTION PERIOD STRAINS IN CABLE STAYS

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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INTRODUCTION

Background

In June 1986, investigators at the Virginia Transportation Research Council began implementing a plan for instrumenting the I-295 cable-stayed bridge during the construction phase with the intent of making continued field measurements of response during the in-service phase. Originally, the plan was to instrument deck segments, piers, and pylons on the south side of the bridge using electrical resistance strain gages mounted on dummy reinforcing bars, cable stays using electrical resistance strain gages mounted directly on the stay cables, and thermocouples. All transducers were to be connected to an automatic data acquisition system. This instrumentation installation has been completed. The data obtained are under analysis and will be the subject of future reports.

The overall objective of this study is to evaluate the behavior and response of the I-295 cable-stayed bridge over the James River near Richmond, Virginia. This investigation and program of instrumentation seek to address a number of questions regarding bridge response for which only limited experimental data are available.

In the summer of 1987, the Federal Highway Administration (FHWA) requested that additional instrumentation be installed to monitor stresses in the major components of the bridge during the construction period. The additional work was initially concerned with data measurements on the north side of the bridge and primarily required instrumentation of the deck segments with mechanical strain gages and instrumentation of selected cable stays with electrical resistance strain gages. A separate work plan covering this supplemental investigation was submitted in November 1987 and approved in December 1987. As construction had just begun on the north cantilever at the time of the FHWA request, investigators immediately began to implement the additional instrumentation in late July 1987.

Objectives

This report documents the work performed on one particular phase of this investigation from July 1987 through April 1989. As of that date, the bridge erection was nearing completion but construction was still in progress on the south cantilever of the main span and closure of the main span had not taken place.

The specific objectives addressed in this report are those initiated by the FHWA in their 1987 request for additional instrumentation. Specifically, this report focuses on strain data obtained from electrical resistance strain gages on selected cable stays on the north cantilever during the erection of the north cantilever.

Description of Bridge

The I-295 bridge is a segmentally erected, precast, post-tensioned, cable-stayed box girder bridge that consists of 31 individual spans, including approach spans. The approach spans are each 150-ft-long precast box girder segments with external post tensioning continuous over 6 spans constructed by the span-by-span method.

The portion of the structure that was the focus of this investigation consisted of the central 7-span continuous section, which includes the 630-ft main span over the river and the 3 approach spans on either side. An elevation sketch of this portion of the bridge is shown in Figure 1. The middle 5 spans of the bridge, including the main span, are supported by 26 cable stays arranged in a single plane harp configuration and emanating from two pylons, one on either side of the river. Cable-stay forces are transferred to the twin box girders through precast delta frame assemblies located between the girder segments at each stay location as shown in the cross-section sketch of Figure 2. Figure 3 illustrates the detail of the cross section at one of the main pier/pylon locations. The main span over the river was constructed as two cantilevers extending from the two piers located adjacent to the pylons and made continuous by a midspan closure pour. Typical main span segments are 10 ft long and weigh approximately 70 tons.

Forces from the first cable stay, stay S1, are transferred to a delta frame located 40 ft from the center line of the pylon on both the main and back spans, with subsequent stays being spaced at 20-ft intervals. This configuration is illustrated schematically in Figure 4. Details of the cable stay assembly are shown in Figures

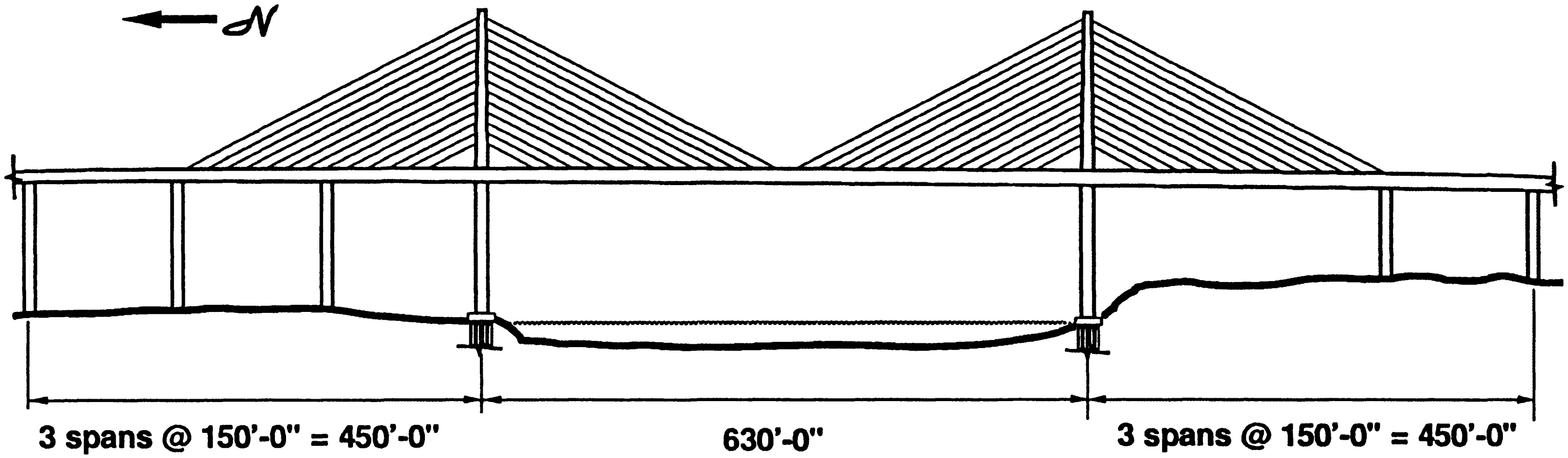

Figure 1. I-295 Bridge Elevation

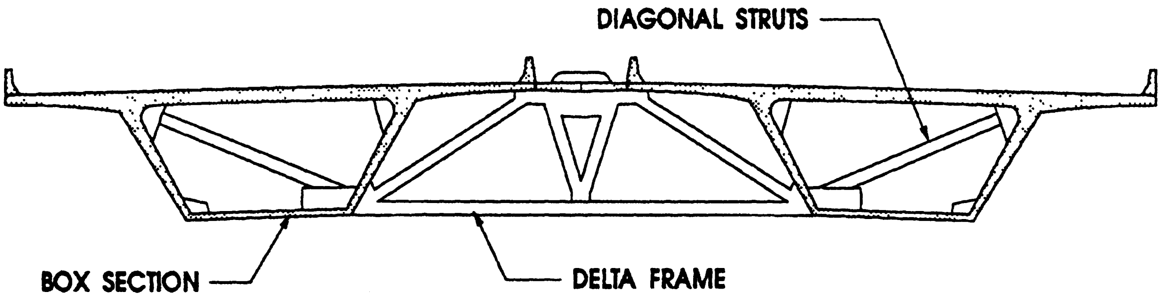

Figure 2. Transverse Cross Section at Stay Anchorage

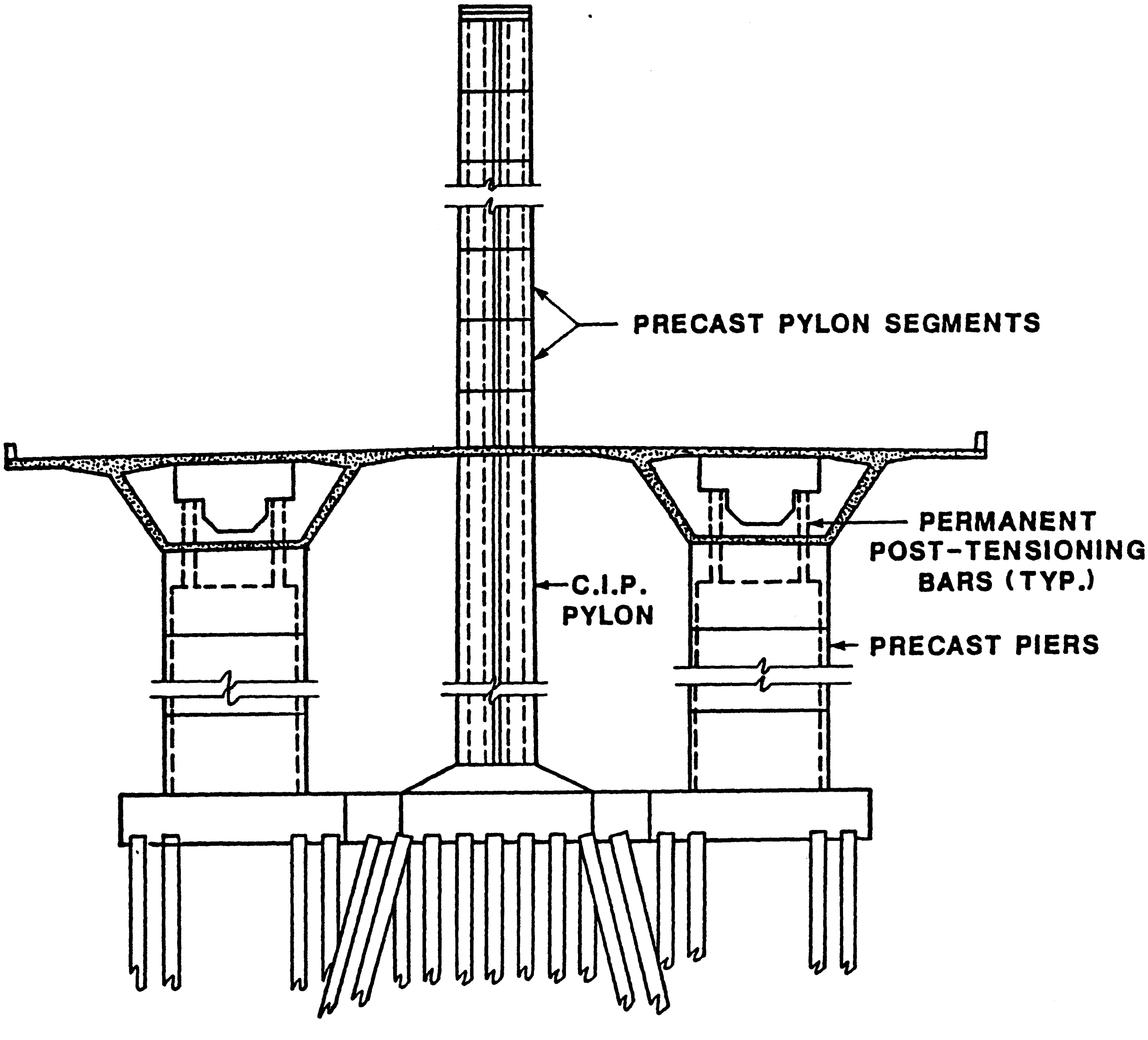

Figure 3. Bridge Cross Section at Pier/Pylon Locations

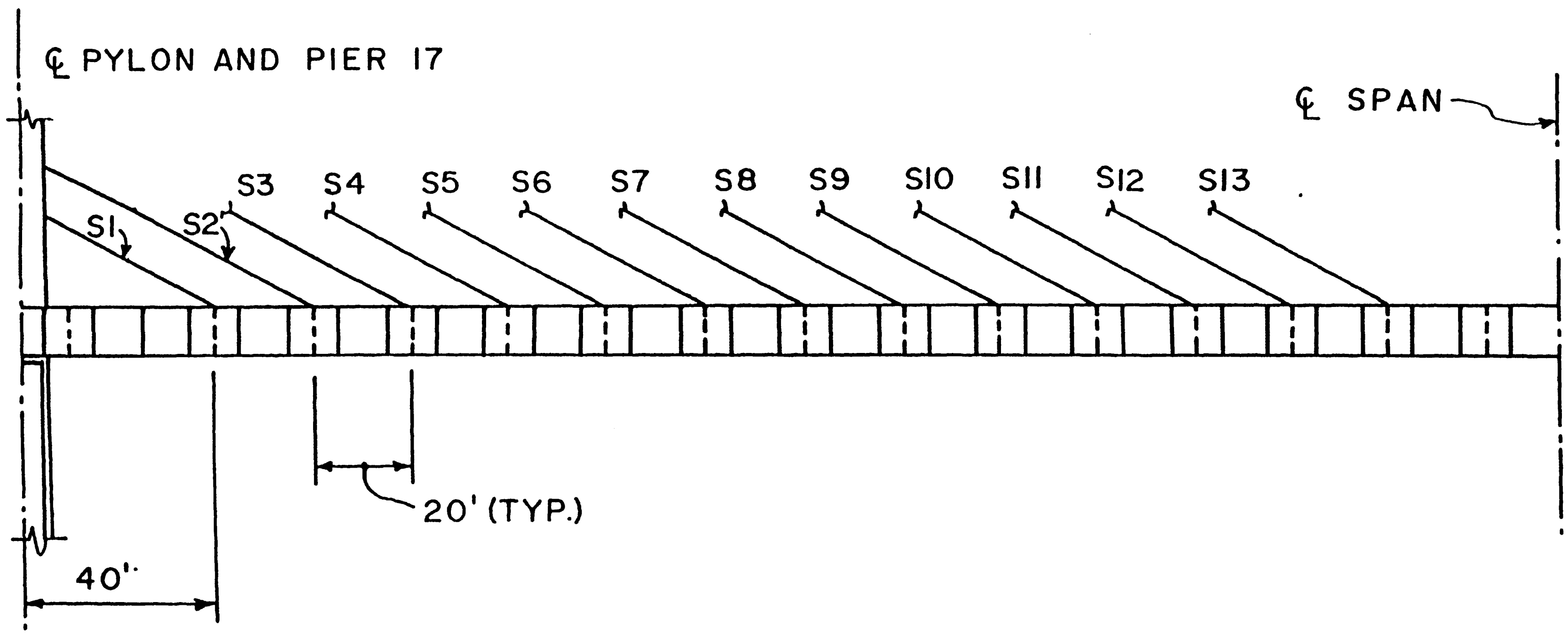

Figure 4. Schematic View of Locations of Cable Stay on North Cantilever

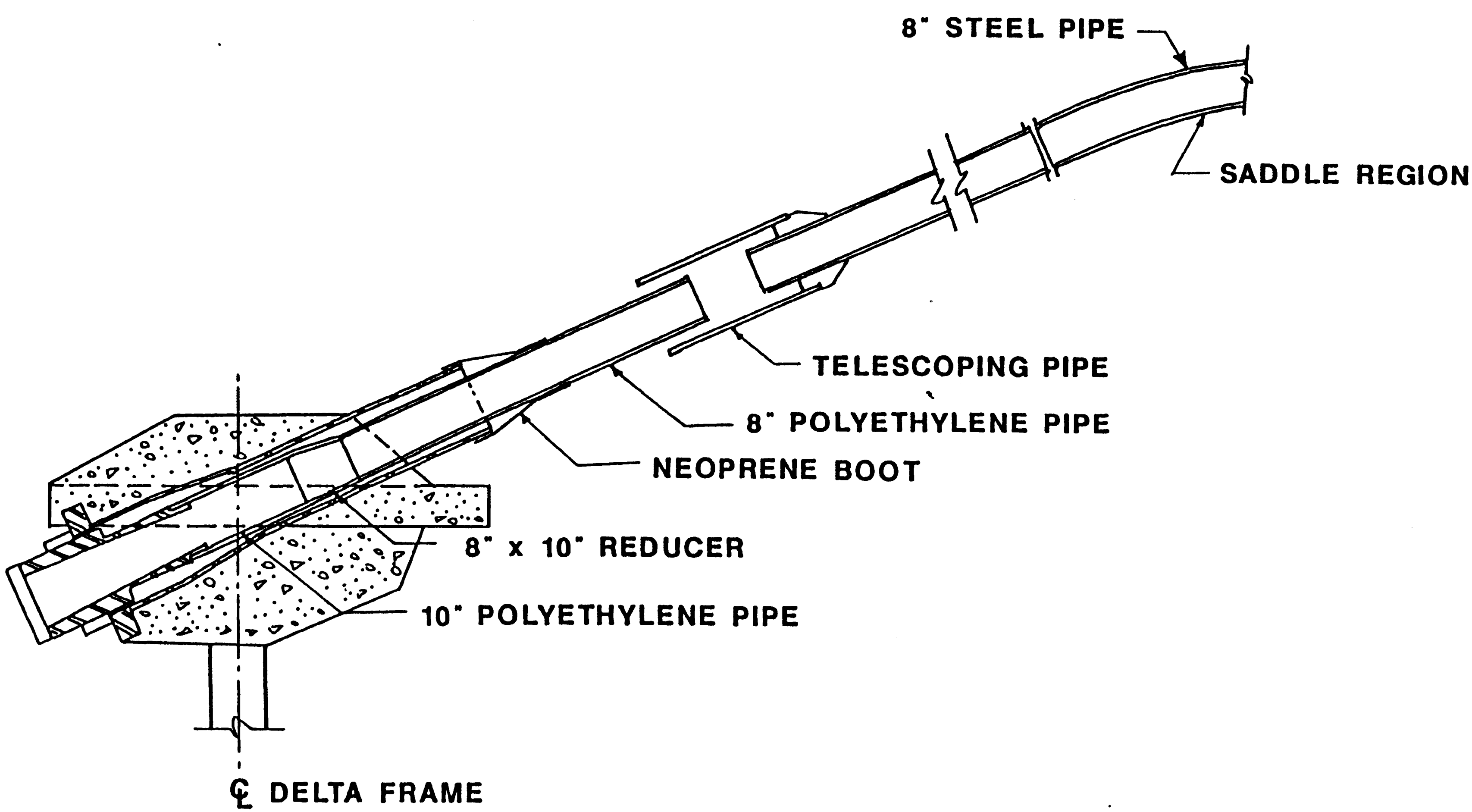

Figure 5. Cable-Stay Assemblage

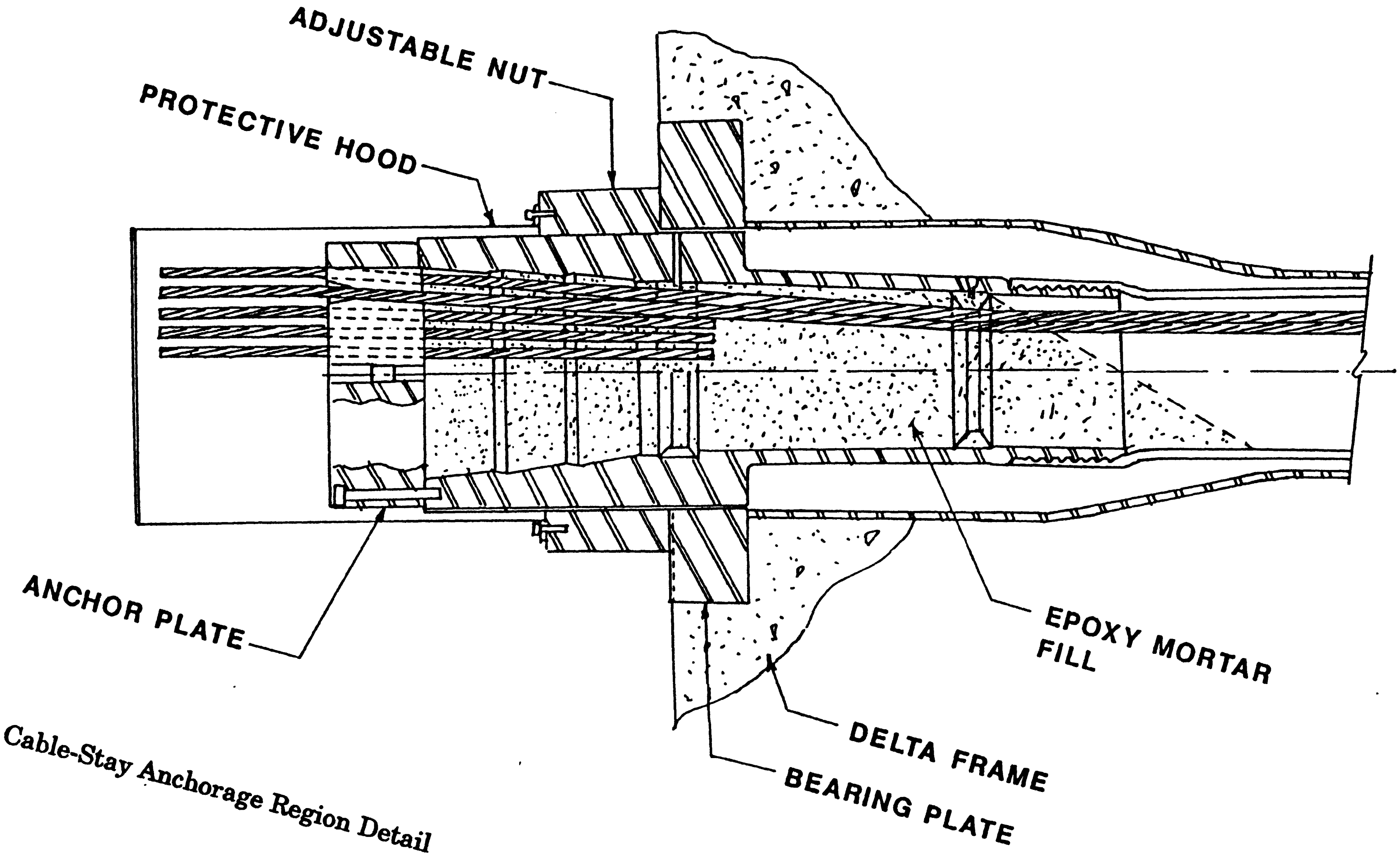

Figure 6. Cable-Stay Anchorage Region Detail

5 and 6. The instrumentation plan for the cable stays, along with other elements of the bridge, is discussed by Baber et al. (1988).

Project Status

At this writing, construction on the bridge is complete. All transducers proposed in both the original and supplemental work plans have been installed, and the data acquisition system is operational. However, the focus of this report is on data gathered during the construction of the north cantilever.

STAY-CABLE INSTRUMENTATION

Electrical Resistance Strain Gages—North Side Stay Cables

A major concern in the long-term performance of a cable-stayed bridge is the satisfactory fatigue performance of the stay cables. As designed, the stay-cable system for the I-295 bridge has between 72 and 90 high-strength steel, seven-wire strands per stay. The tendons are encased in a polyethylene pipe and grouted with a portland cement mortar to provide corrosion protection. To minimize the amount of live load stress taken by the anchorages, the anchorage zone is filled with a steel ball/epoxy grout mixture as the first stage of grouting.

Since the strains in the stay cables are one of the major response quantities of interest, direct instrumentation of the stays appeared to be the most desirable approach, after various alternatives were considered (Baber et al., 1988). Originally, the investigators were asked to install electrical resistance strain gages on 3 of the 13 cable stays (stays S2, S7, and S13). However, since this type of gage installation is identical with that used on the south side as part of the original instrumentation, and since very little information could be found in the literature pertaining to field instrumentation of cable stays, it was decided to instrument additional stays (S1 and S5) to allow the problems associated with the field application to be worked out and to provide additional backup in the event gages were lost. This proved prudent since both eventualities occurred.

On the north side, foil electrical resistance strain gages were mounted directly on the wires in the strands of stays S1, S2, S5, S7, and S13. To provide for a reliable determination of average strains in the cables, and to provide some indication of strain distribution throughout the cable cross section, a number of gages were placed on each stay cable. After initial experimentation with different lead wire and dummy gage configurations, it was decided to use a temperature-compensating dummy gage, mounted on a short length of prestressing wire identical with the cable-stay strand and located adjacent to the active gage in the cable-stay duct. The active and dummy gages were independently wired with two wire leads. On stays S1 and S2, eight gages were installed, two on each of four strands. There appeared to be a significant tendency for some strands to shift positions or twist during tensioning, causing loss of gages, so it was decided to only use one strain gage on each strand for subsequent stays. On stay S5, four gages were installed on four separate strands. Eight gages were installed on stays S7 and S13, but on eight different strands. Sketches of the stay instrumentation are shown in Figures 7 and 8 and further details of the procedure used for mounting, wiring, and waterproofing the gages were discussed by Baber et al. (1988).

All of the gages on all stay cables were independently wired to maximize reliability under field conditions, with all averaging of data to be done during the analysis phase. The lead wires from the active and dummy gages were led out of the polyethylene pipe through the expansion joint prior to tensioning of the stay. On the north side of the bridge, these lead wires were then run to switch and balance units where strains were read manually using a strain indicator unit.

Gage Installation Difficulties and Suggested Solutions

The gage installation design was selected to provide tensioning, construction period, and service life data. Since the variety of data to be gathered could be obtained only over an extended time period, it was necessary to plan the gage installation for maximum durability. Hence, the investigators chose to use epoxy adhesives. This choice created severe problems in installing the gages, as the strain gage grade epoxy adhesive chosen will not cure below 70°F and requires at least 6 hr to cure under those conditions. Accelerated curing could be achieved, but only by using a heating blanket that locally raises the temperature significantly. Under field conditions, either very low temperatures that made artificial heating a necessity or very high ambient temperatures that reduced the pot life of the epoxy were routinely encountered. The situation was further complicated by the relatively short period of time available to complete the instrumentation. Typically, the investigators would be able to access the stay cables in position within the polyethylene ducts no more than 24 hr before tensioning. In several instances, the investigators could not obtain confirmation of the date of installation of a cable stay until roughly 1 day before the stay was actually pulled through the duct.

A possible solution for this problem would be to install the gages twice. Using a quick-acting adhesive, such as cyanoacrylic glue, a quick installation could be obtained prior to tensioning. This set of gages, which would have limited durability, could be used to provide estimates of the strains during tensioning. Subsequent to tensioning, when more time is available for curing slow adhesives, a second installation could be undertaken. This installation would be calibrated with the first set of gages and would then replace those gages for subsequent readings. This approach was not followed during the present project, but this method might be suitable for future installations of this type.

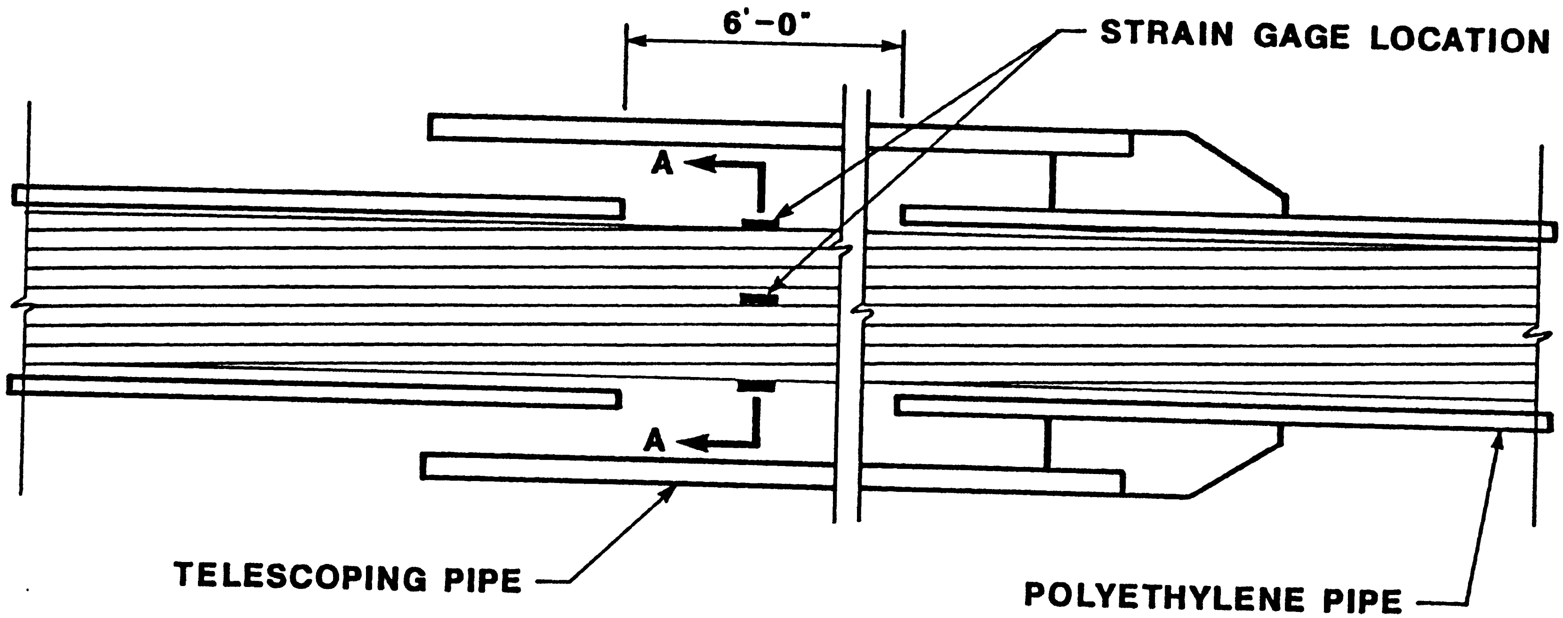

Figure 7. Location of Strain Gage Within Stay Duct

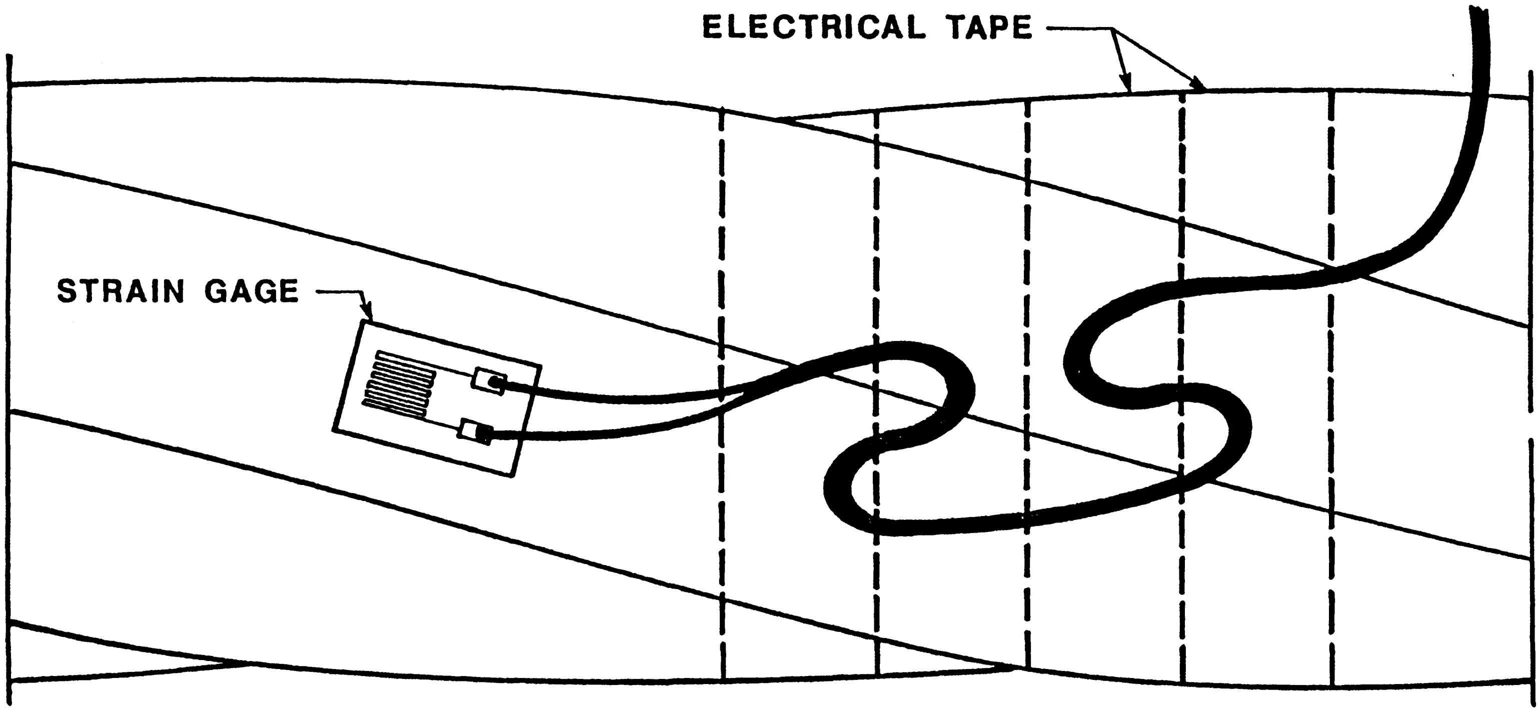

Figure 8. Location of Strain Gage on Typical Seven-Wire Strand

A second difficulty was recognized fairly late in the project and was resolved for the final installation of gages for the live load studies. In all early applications, separate two-wire leads were used for both the active and dummy gages. In the tensioned configuration, it was quite difficult to find a secure place for the dummy gages to be located where they would not be disturbed and damaged by the grouting activities. Consequently, a revised lead wire configuration was developed, as shown in Figure 9. A single three-wire lead was used. The jacketing was stripped off over a length of approximately 2 in near the active gage end. One of the leads was cut at this point and connected to the dummy gage that was mounted on a length of prestressing strand approximately 1 in long. This dummy gage was then waterproofed in place using a layer of epoxy, a layer of polysulfide waterproofing, and a carefully applied wrapping of vinyl electrical tape. The end of the three-wire lead was then stripped and prepared for attachment to the active gage in the field. The wire that had been attached to the dummy gage was twisted together with a second lead wire and attached to one terminal of the active gage. The remaining lead was attached to the other active gage terminal. The resulting temperature-compensating gage installation required only a single three-wire jacketed conductor, and the dummy gage was located securely in line, with the lead attached to the active gage. This installation method appeared to be superior to the original installation method used during the final grouting stage.

Electrical Resistance Strain Gages—South Side Stay Cables

Techniques for instrumenting the stay cables were developed using the stay cables on the north cantilever. Based on the experience gained during this instrumentation, a consistent procedure for instrumenting the stays was employed with the south side stays, which consisted of mounting foil-resistance strain gages directly on the wires in the strands making up the stay cable. Even though this process had been practiced with the north side stays, problems were still encountered.

Three stay cables, stays S2, S7, and S13, were instrumented with electrical resistance strain gages with eight gages installed on each stay. Each gage was installed on a different wire in the strand in order to provide for a reliable determination of average strains in the cable. Access to the stay was by means of the expansion joint provided in the polyethylene pipe as shown in Figure 7, and lead wires from the gages exited through this expansion joint directly to the data acquisition system located in the box deck segment. This required embedding lead wires for splicing through the concrete superstructure into a blockout in the segment.

Data Acquisition—South Side Stays

The data acquisition system, manufactured by the John Fluke Company, uses a Helios main controller to communicate with a number of individual remote

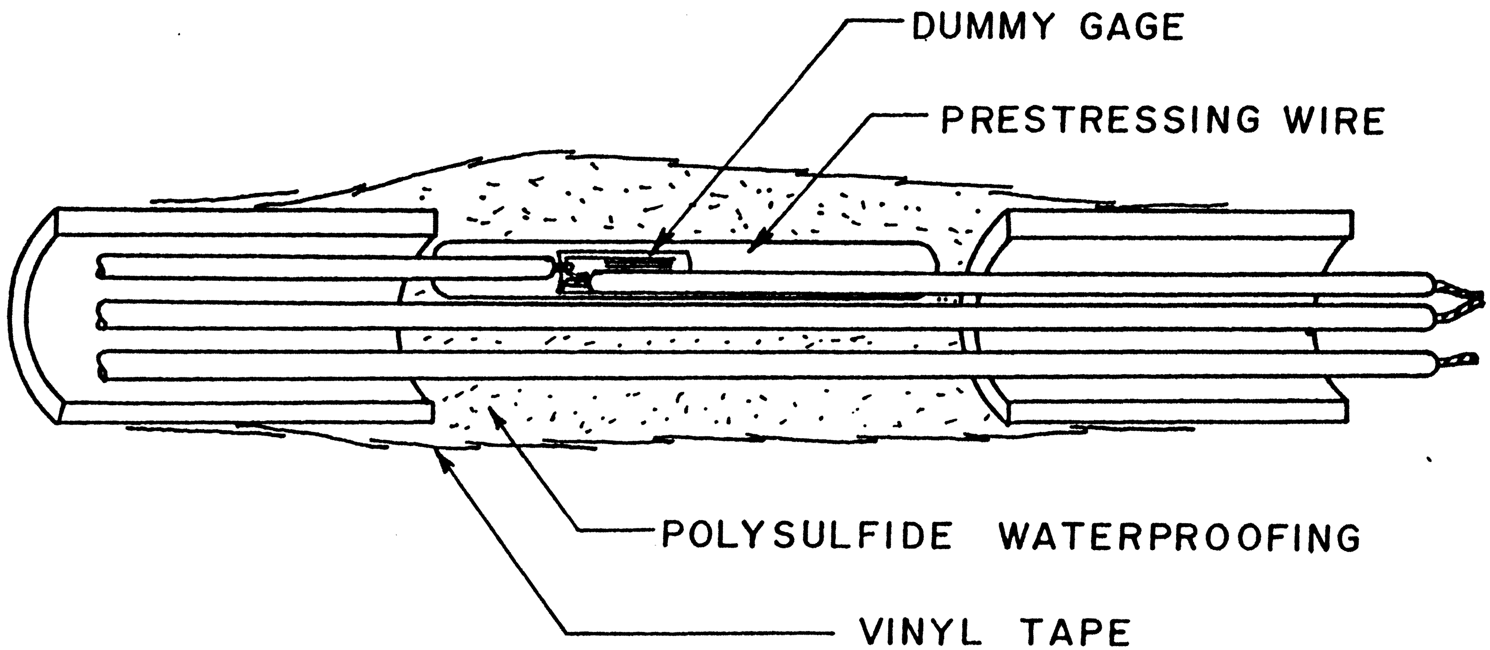

Figure 9. Modified Lead Wire/Dummy Gage Configuration for Live Load Studies

scanning units, each of which is located near an instrumented section in an extender chassis. The Helios controller, and an associated personal computer, are located in a specially designed and fabricated cabinet, which is provided with complete environmental controls and which also serves to provide security for the equipment.

The lead wires from strain gages on the stay cables were connected either to the Helios or to one of four extender chassis. Each extender chassis has its own A/D converters, and the digitized data from each extender chassis are transmitted to the Helios controller via RS422 cables. The Helios then sends the data to the controlling personal computer where it is logged into Lotus 1-2-3–formatted data files for subsequent analysis. Specially designed software permits data sampling and recording at regular intervals as prescribed by the investigators. Further details of the data acquisition system were discussed by Baber et al. (1988).

RESULTS AND DATA ANALYSIS

Scope

In this section, results obtained primarily from electrical resistance strain gages on the stay cables of the north side are presented and discussed. Installation of all gages has been completed, including additional strain gages mounted on stays S7 and S13 of the north half of the bridge specifically for live load strain measurements.

Strains in North Cantilever Stay Cables

General Discussion

This section summarizes the construction strain variations measured in the north cantilever cable stays. All strain readings on the north side of the bridge were taken manually using a switch and balance unit and strain indicator. On several of the cable stays, thermocouples were located at a number of locations around the stay to provide the investigators with thermal information. The investigators encountered several problems in acquiring the data on the north side stay cables, including loss of gages during tensioning, shifting of the slack stays prior to tensioning, thermal changes induced by solar heating and wind cooling on the leads, and sensitivity of the strain indicator and switch and balance units to the connections of the individual leads. With the exception of the loss of gages during tensioning, all of these problems were resolved; thus many of these problems should not be encountered with the south side data collection and during subsequent live load studies.

The scheduling and timing of all strain readings were important. This was particularly true for the strains in the stay cables. As with the gage installations, scheduling readings also proved difficult to arrange for a number of reasons. Ideally, strain readings should be obtained immediately before and after major construction activities such as tensioning a cable, installing a girder post tensioning, and lifting a segment. In addition, the investigators considered it desirable to record strain readings on a regular basis, preferably at least once a week, even if no construction activities had taken place. When the instrumented stay was being tensioned, it was planned to take regular readings during the tensioning procedure. Although most of these objectives were achieved, a number of nagging problems did cause difficulties with the data collection.

The physical distance from Charlottesville to the bridge site often made a quick response to construction activities difficult. Also, the need for frequent data collection necessitated that readings be taken by a number of different personnel. The wiring and strain indicator system appeared to be quite sensitive to a variety of factors. In particular, electrical noise caused by construction generators appeared to lead to some fluctuation in the readings. Moreover, the gages appeared sensitive to quite small changes taking place on the bridge. In addition, temperature changes induced by solar heating and wind cooling appeared to change the readings somewhat. This latter effect was largely eliminated by the installation of dummy gages in each stay cable. The data, once recorded, were entered into Lotus files on a personal computer for subsequent analysis.

A large amount of data was collected, as there were five instrumented stays, and typically, after the expected loss of some gages during tensioning, roughly five gages per stay. All active gages were read every time a significant change took place on the bridge. It was found to be impractical to take gage readings after every change of the structure since this would have required one of the investigators to be on the bridge to take cable-stay readings essentially all the time. Thus, it was decided to take readings immediately before and immediately after tensioning of a stay cable. These readings could be taken fairly efficiently and tended to reflect the major response variables. The "before tensioning" readings showed the influence of the newly hung girder segments and delta frame, whereas the "after tensioning" readings revealed the strain changes in all active stays induced by tensioning a single additional stay.

For present purposes, it appeared to be most desirable to plot the data in a form that would reflect the time-varying nature of the strains during the construction period. After some preliminary analyses, it was decided to plot strain or strain increment as a function of time to illustrate changes in strain in the stay cables attributable to stay tensioning, segment lifting, and other construction activities. Ideally, this simple presentation also permits an evaluation of stay-cable response during the actual tensioning of the instrumented stay.

The data to be presented and discussed subsequently are shown plotted in Figures 10 through 46. Typically, each graph covers a 1-month period except in certain cases where a break in the data made a different time scale more convenient. The vertical axis is labeled as average relative strain. The readings are relative in the sense that the zero strain level was lost during the study. Since the zeros were lost in several cases, the measured "absolute" strains ceased to have significance. To accommodate for this problem, the various strain readings recorded over time using different instruments were normalized with respect to the same reference. Thus, except as noted, the strain readings plotted in the various figures should not be interpreted to be absolute. In most instances, the changes in strain attributable to a particular event are of greatest interest, and these data were obtained without significant problems.

All readings were taken with a single strain indicator. The individual gages were connected to several switch and balance units, which were connected to the gage lead wires and left in the field, protected by metal boxes. Initially, when stays 1 and 2 were instrumented, the switch and balance units on those gages were adjusted to read zero strain in the slack state. Several strain readings were taken on stays 1 and 2 using those initial settings with no dummy gages. The initial readings taken during tensioning appeared to be reasonably stable. It was subsequently discovered that the wiring scheme was very sensitive to thermal changes, primarily caused by resistance changes in the lead wires. To eliminate this problem, dummy gages were installed on each of the switch and balance units. The data were subsequently stabilized, but unfortunately, the zero reading was lost when the wiring scheme was changed. Stay 5 was initially wired with a single dummy gage, which continued to function throughout the erection period. Consequently, the zero readings established using the switch and balance unit on the stay 5 gages are considered to be good. Considerable shifting of the strands was observed before and during tensioning, however. Stay 7 also had a single dummy gage installed that functioned adequately during tensioning, and for some time thereafter. That dummy gage failed and had to be replaced during the tensioning of stay 9. Consequently, after that dummy gage was replaced, all strain readings on stay 7 were relative rather than absolute. In spite of these difficulties, valuable data were obtained. In particular, the changes in strain during a tensioning or segment-lifting activity appeared to be measured relatively consistently by all gages on a single stay cable and the changes are of absolute, rather than relative, significance.

Proper evaluation of the cable-stay strain data requires a knowledge of exactly what events took place within a particular time frame. For this purpose, an accurate and up-to-date construction schedule was maintained by the research team. The major construction activities are labeled on the graphs of the cable stay strain data to facilitate the interpretation of the changes in strain. Care should be taken in interpreting the data, however, since the changes in strain indicated on the graphs may be attributable to a number of construction activities that occurred within a very short period of time. These will be pointed out in the discussion of the individual stay data that follows. The data that follow reflect strains measured in stays 1, 2, 5, 7, and 13 on the north side from the time each stay was pulled and tensioned until the last stay, stay 13, was installed in December 1988. For convenience, data recorded from gages on each stay are presented and discussed individually for each stay.

Stay 1 Data

Figures 10 through 19 depict the average measurements of changes in strain in stay cable 1 from the period March 16, 1988, when stay number 1 was initially tensioned, until December 1988 when the last stay on the north side, stay 13, was installed. Except for the initial data in Figure 10, which reflects strain measurements taken before dummy gages were added, each figure represents strains recorded during a particular month. As noted previously, the addition of the dummy gage caused an indeterminate shift in the baseline. A rough correction is possible based on the last reading before the addition of the dummy gages, but this correction was not considered desirable, or necessary, since the changes in strains caused by subsequent events are of primary interest. The relative strains plotted represent the average of all active gages on the stay. Variations in these gages are discussed in a subsequent section. Examination of the data in these figures indicates several interesting features worth noting.

On this particular stay, the strands were pushed through the polyethylene ducts individually, rather than being pulled through as a group. The gages were installed as soon as the strands were in place within the ducts and prior to tensioning. Thus, it was possible to take readings continuously during the tensioning process. As shown in Figure 10, five average strain readings were recorded while the stay was being tensioned. The five values plotted on the graph correspond to average strain values of 0, 288, 523, 1,960, and 2,485 microinches per inch. There is some uncertainty in the intermediate readings, as the tensioning process was continuous and the pressure in the pretensioning jacks continued to vary while the readings were being taken. Based on laboratory studies using identical gages and prestressing strand segments, when the gages are mounted on an angle on individual wires, the effective modulus of elasticity is on the order of 33 million psi, then the total tension imparted in the stay was approximately 82,000 psi, which compares favorably with the initial target tension of 82,500 psi listed in the plans.

Approximately 2 weeks later, stay 2 was installed and tensioned and, as shown in Figure 10, this caused a decrease in the strain in stay 1 of approximately 380 microinches per inch. On April 19, stay 3 was tensioned and, consistent with earlier observations, the strain in stay 1 was again reduced by approximately 360 microinches per inch. This same pattern was observed on all subsequent stay tensioning except that the strain reduction diminished with the distance of the tensioned stay from stay 1.

The data from Figures 11 through 19 also indicate that erection of additional segments caused slight increases in the average strain readings, although these increases were generally not significant. This is not seen in Figure 10, when the addition of segments 5 and 6 was accompanied by an apparent decrease in stay force. In this instance, the addition of temporary and permanent post tensioning to the top slabs appears to have counteracted the weight of the added segments. This result was not observed on any other stay, which is also logical, since stay 1 is close to the piers and temporary post tensioning at this stage extended beyond the piers.

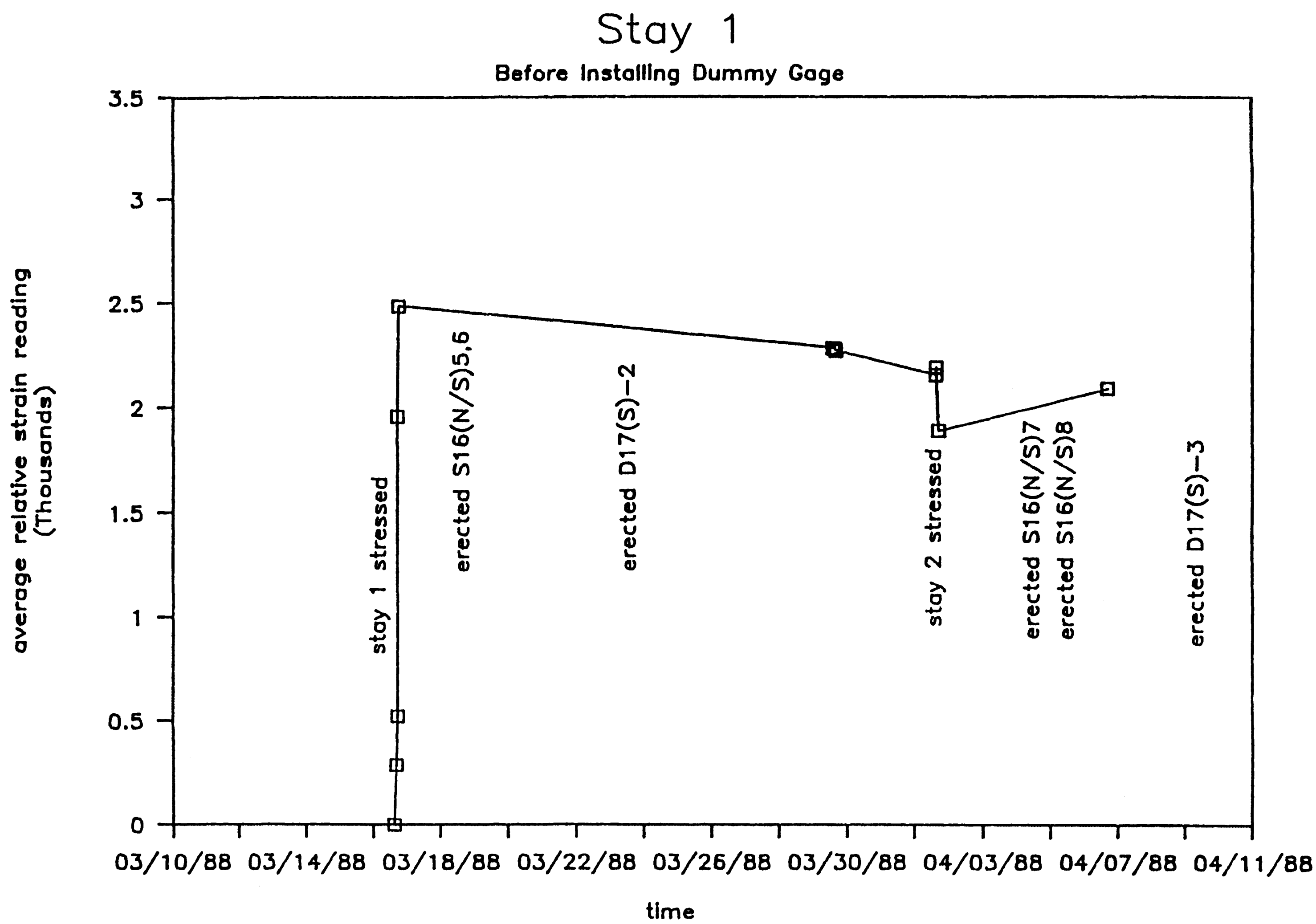

Figure 10. Stay S1, Average Strain Data Before Installation of Dummy Gages

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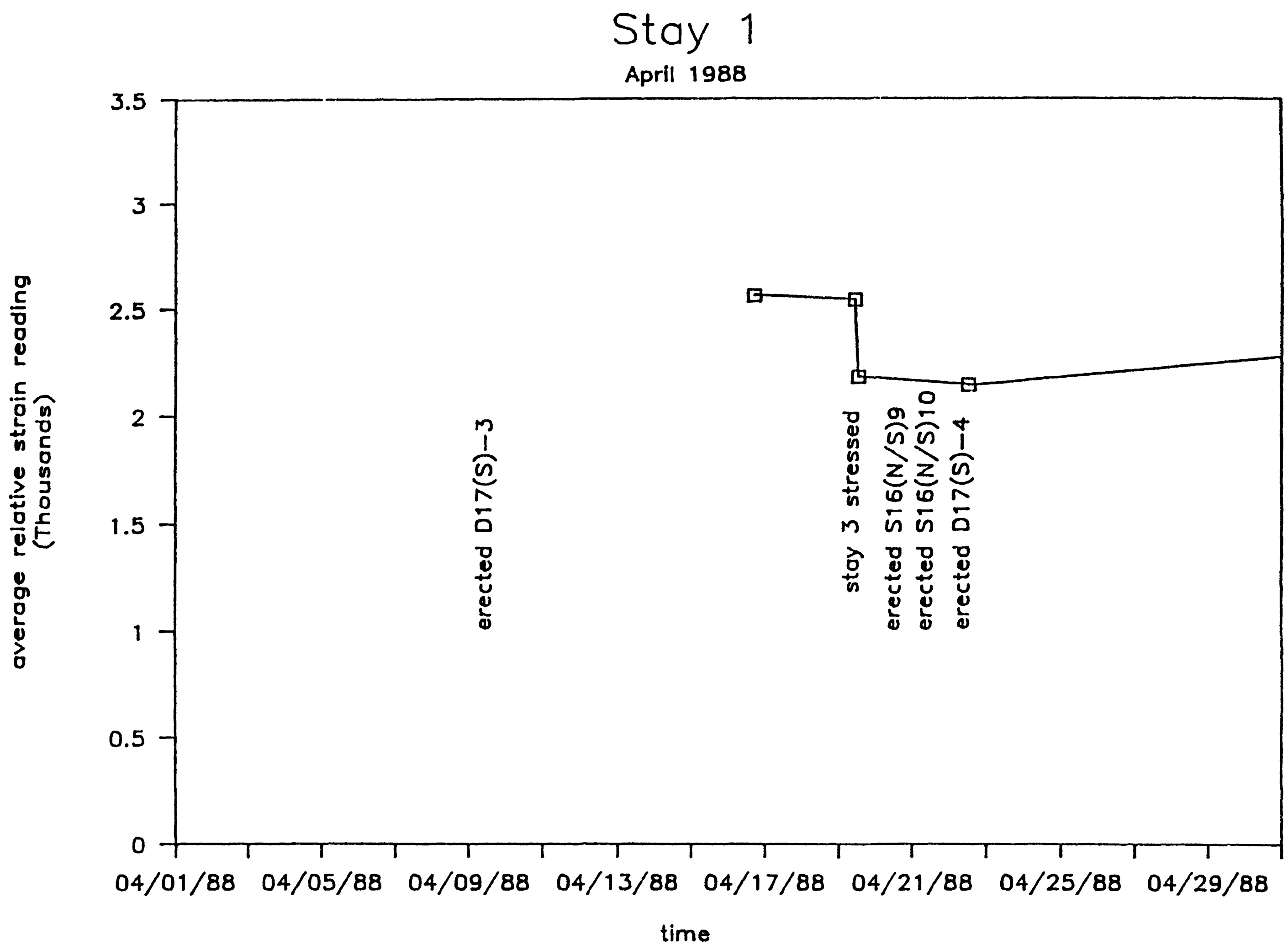

Figure 11. Stay S1, Average Relative Strain Data, April 1988

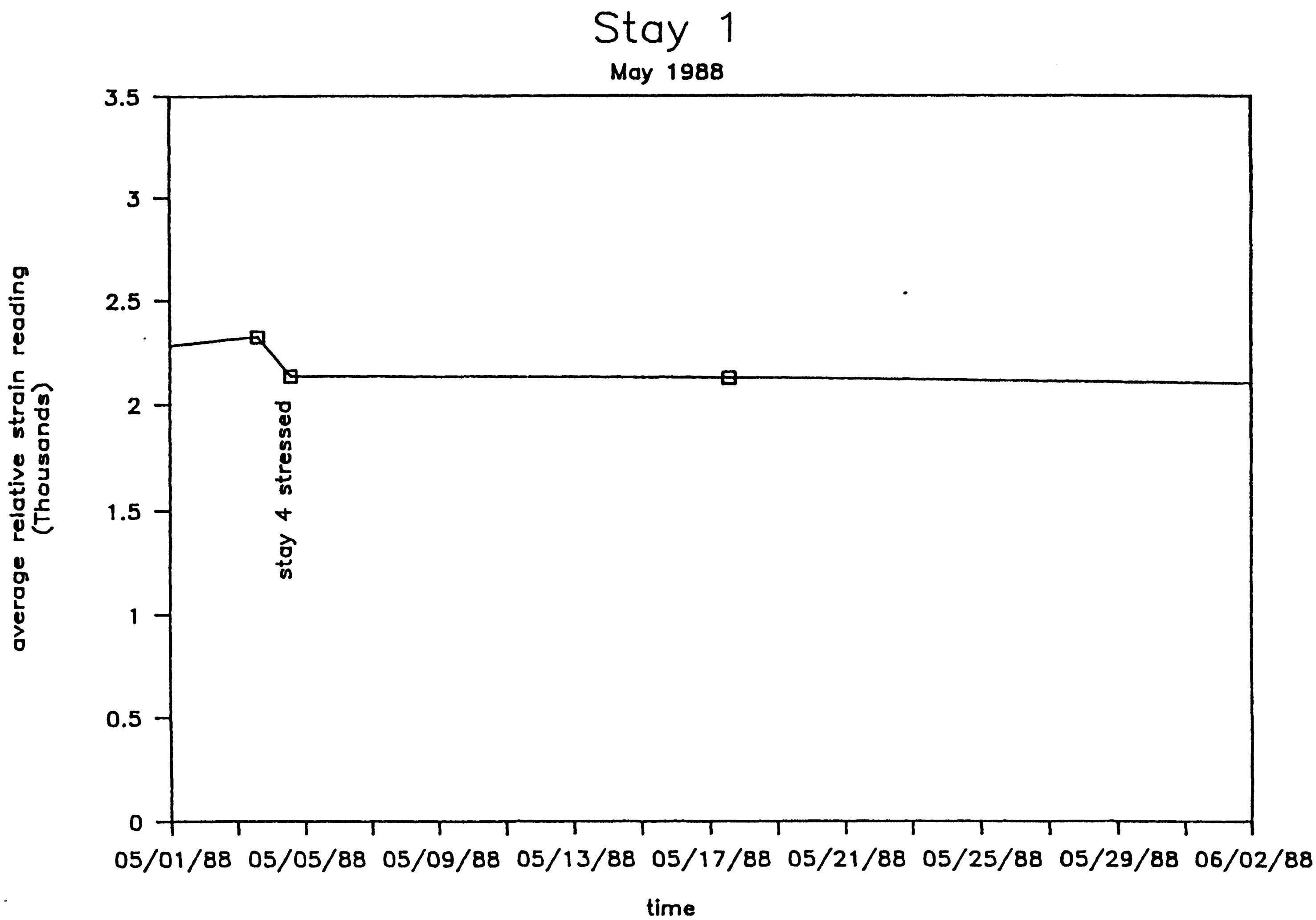

Figure 12. Stay S1, Average Relative Strain Data, May 1988

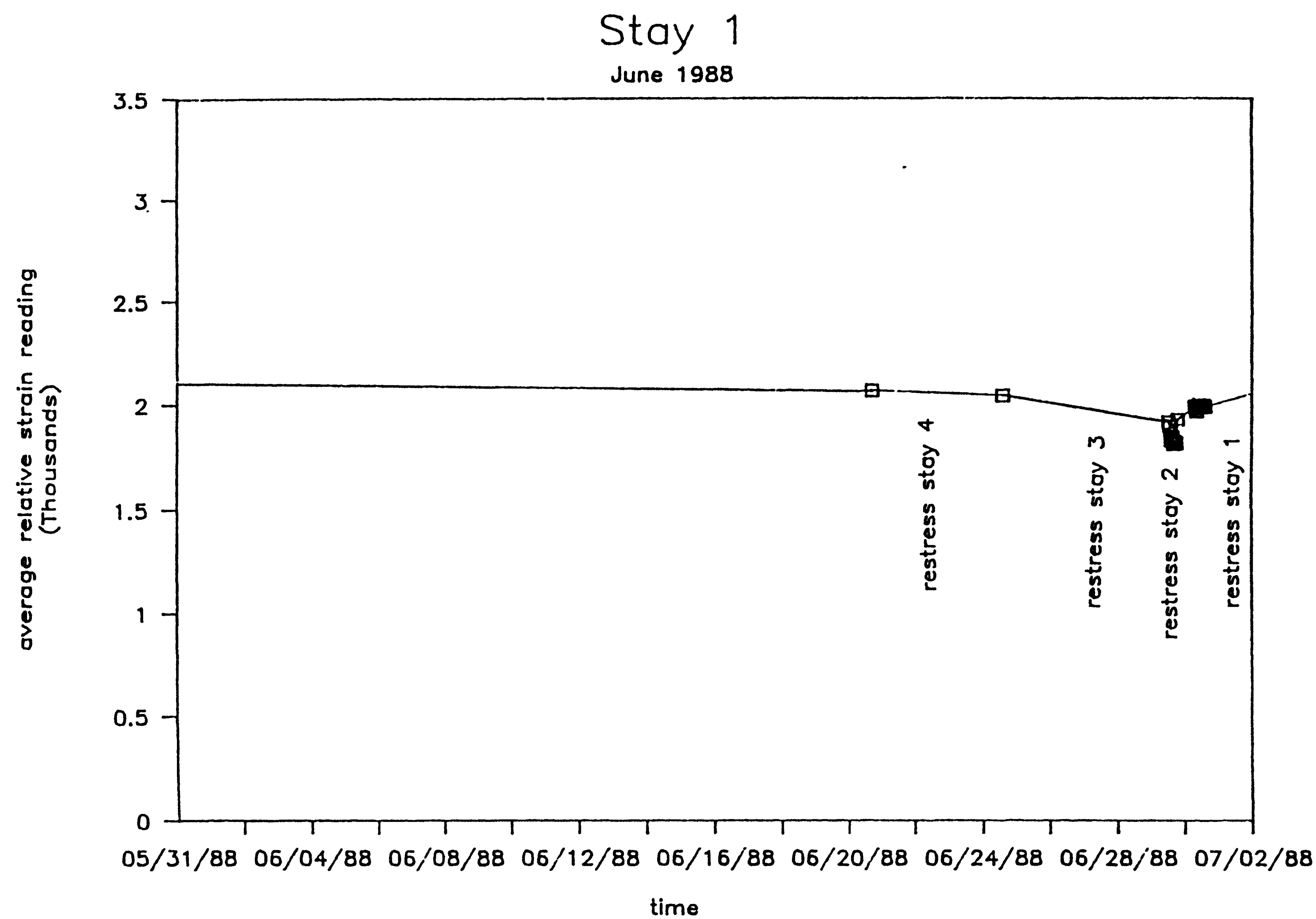

Figure 13. Stay S1, Average Relative Strain Data, June 1988

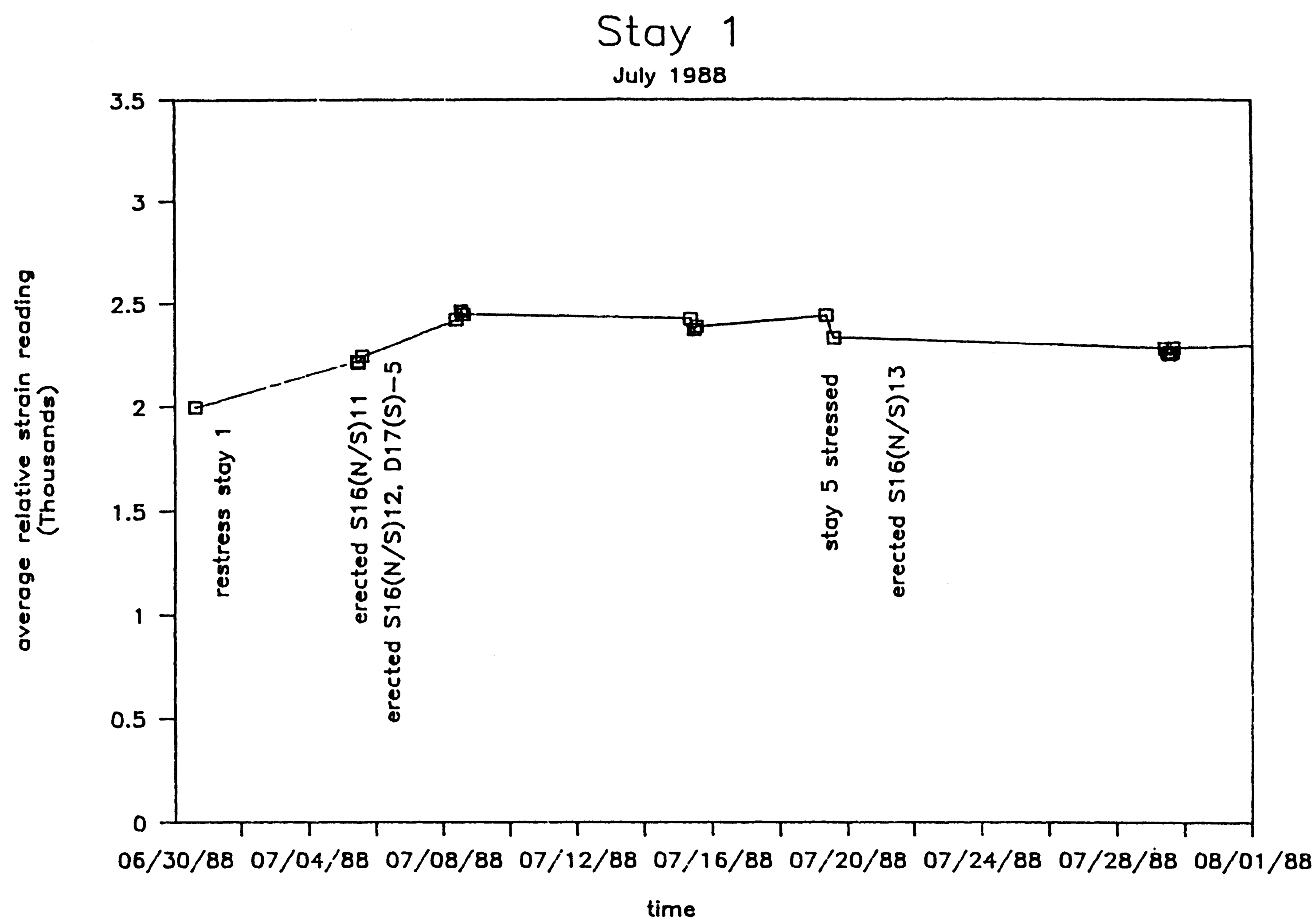

Figure 14. Stay S1, Average Relative Strain Data, July 1988

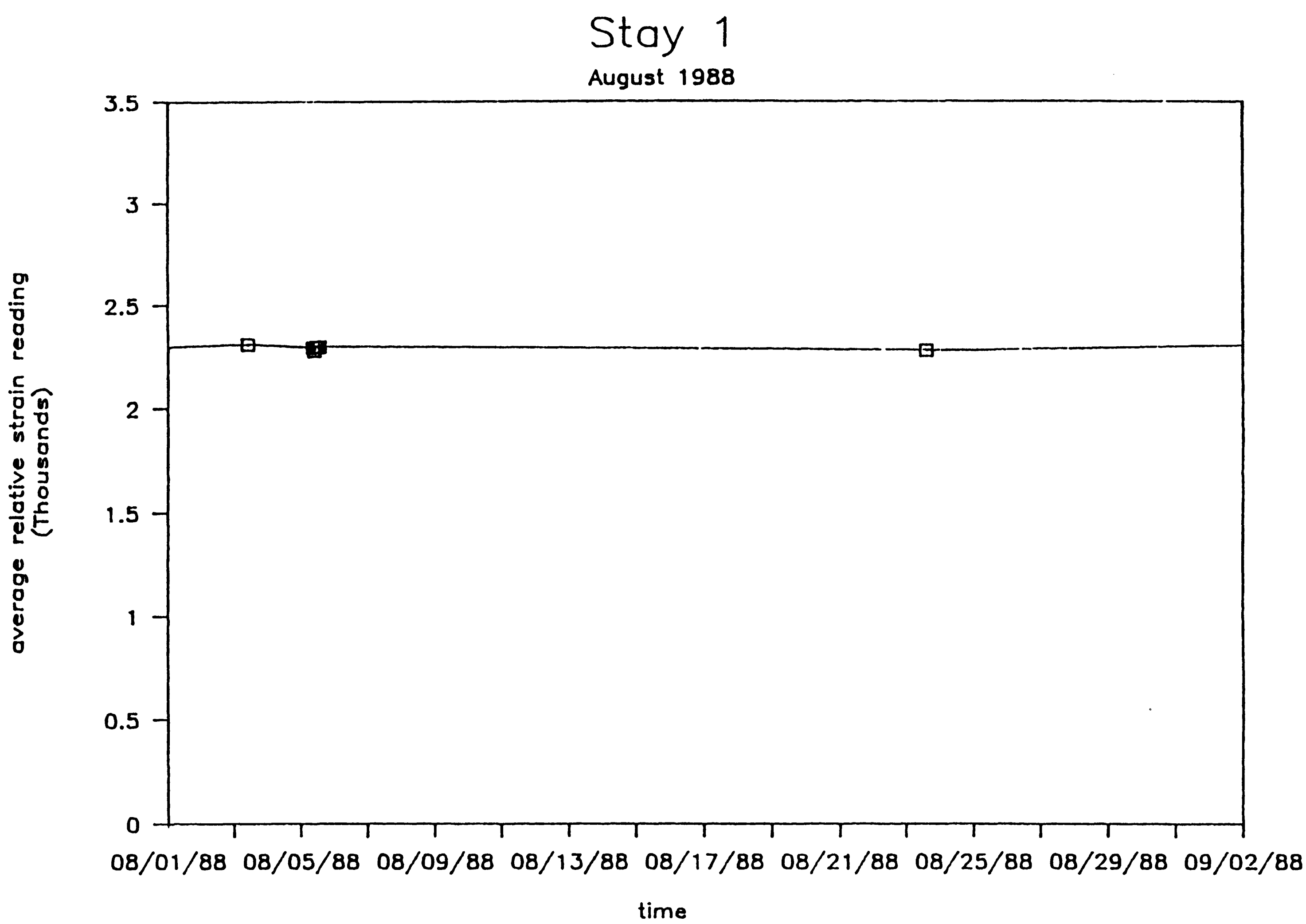

Figure 15. Stay S1, Average Relative Strain Data, August 1988

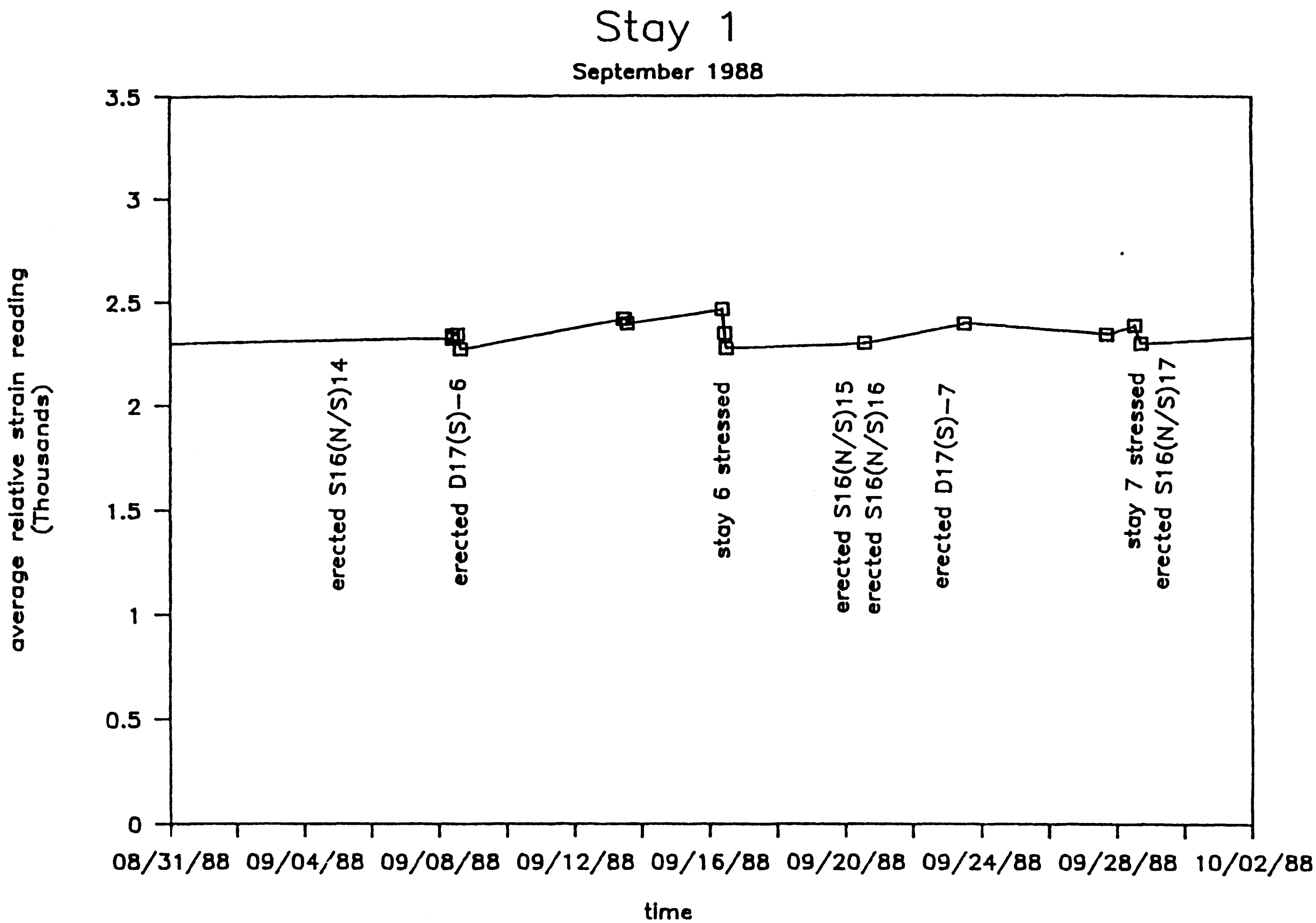

Figure 16. Stay S1, Average Relative Strain Data, September 1988

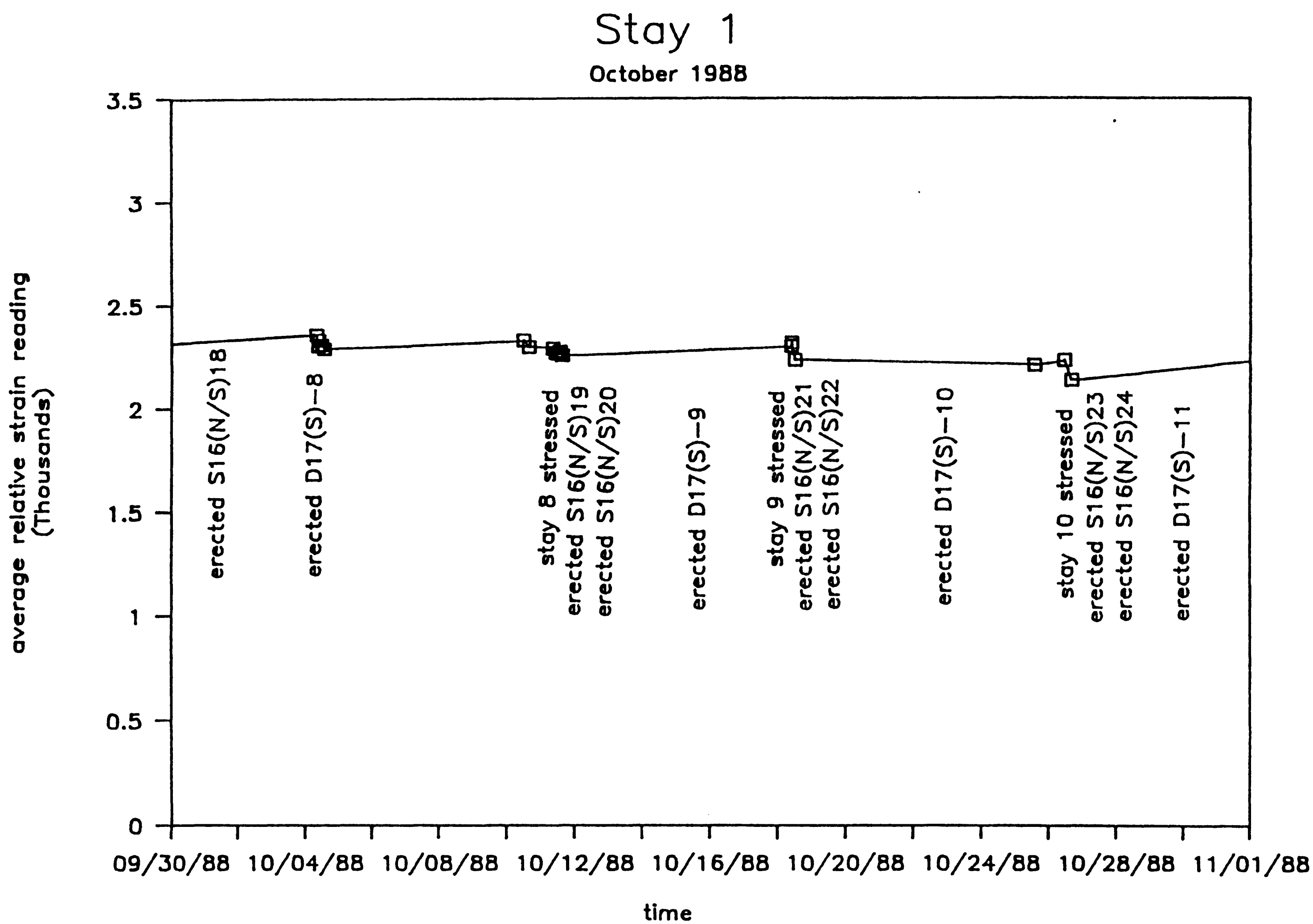

Figure 17. Stay S1, Average Relative Strain Data, October 1988

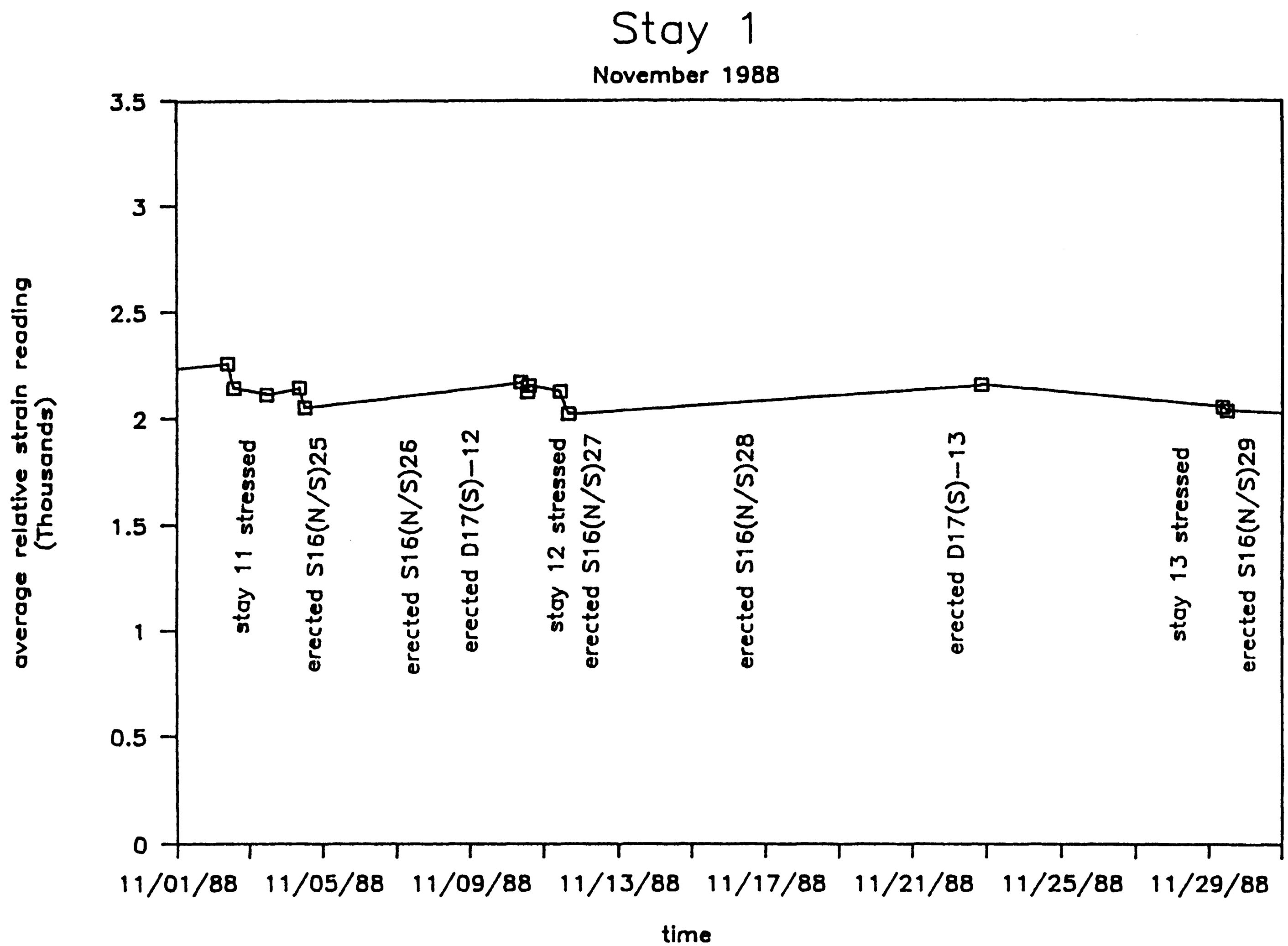

Figure 18. Stay S1, Average Relative Strain Data, November 1988

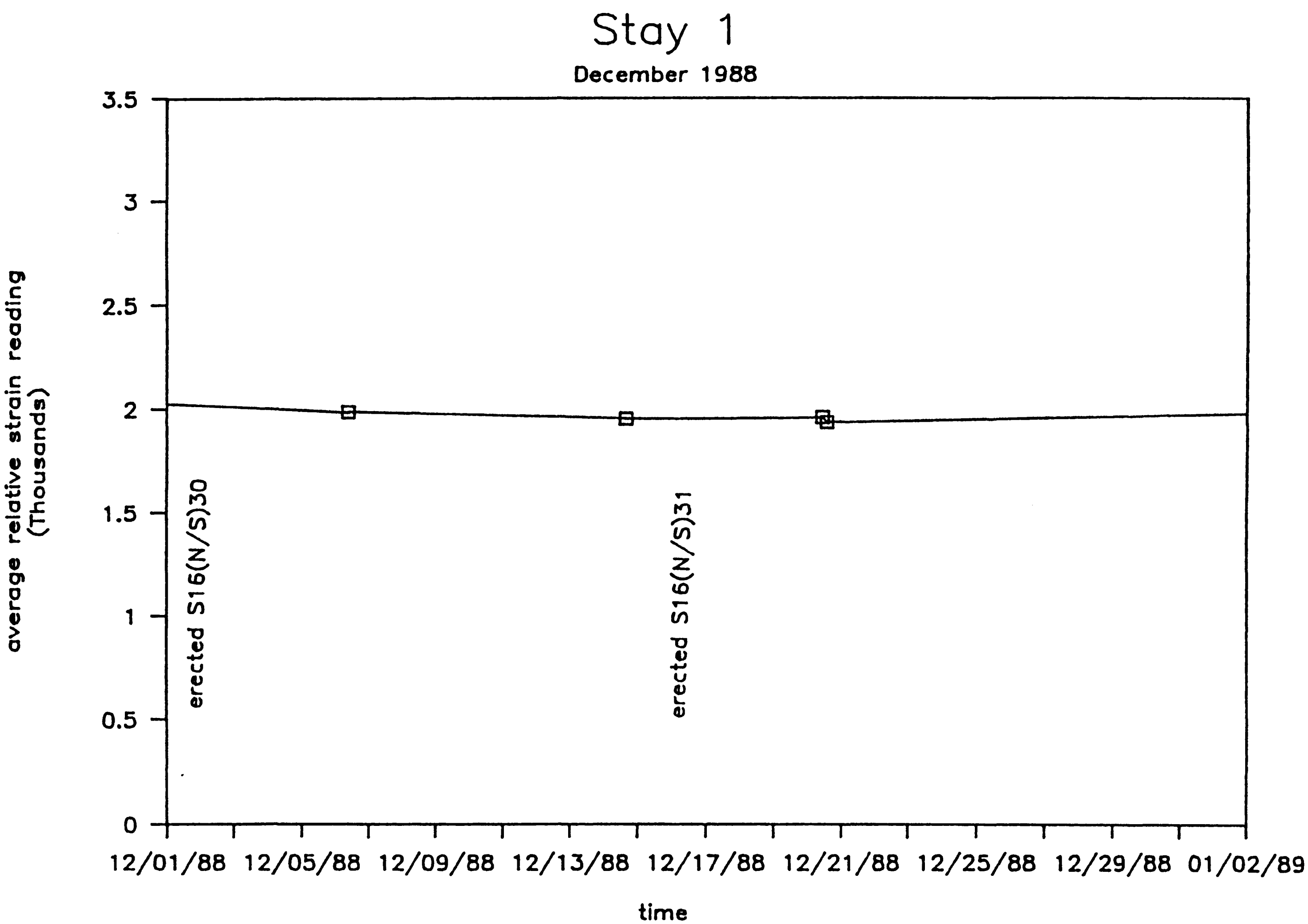

Figure 19. Stay S1, Average Relative Strain Data, December 1988

Subsequent construction activities included eventual removal of the temporary post tensioning, a lengthy period of construction stoppage, and the restressing of stays 1 through 4. During this entire period, the strain changes measured were well within the expected levels.

Stay 2 Data

Average strain data from stay 2 are provided in Figures 20 through 29. This stay was installed one strand at a time, as was stay 1, and was tensioned on April 1, 1988. The average change in strain introduced by the tensioning process is indicated in Figure 20, based on the average of four gages. From the time the jacks were in place and set to load until the tensioning was completed, a period of less than 15 min, there was an increase in strain of approximately 2,150 microinches per inch. This corresponds to an increase of almost 2,500 microinches per inch measured on stay 1 when it was tensioned. As was observed with stay 1, tensioning of subsequent stays produced a slight decrease in the strain of stay 2, as may be seen in Figures 21 through 29. These reductions in strain are relatively small, usually on the order of 300 to 400 microinches per inch or less.

From these figures, it also appears that the erection of additional segments between stay 2 and stay 3 caused very slight decreases in the strain in stay 2. As discussed previously, erecting additional segments was not the only activity that occurred between the strain data recordings that produced the strain increment plotted. For example, when a segment is added, a significant portion of the load is supported by the post tensioning in the deck, both by the tendons in the ducts in the deck slab itself and in the Diwidag bars. Moreover, some post tensioning was added soon after the cable-stay stressing operations. If one takes into account the load imparted by the post tensioning, which is comparable to the load in the stay cables, the decrease in strain in the stay cables attributable to erecting more segments appears reasonable. It also appears that this effect would not be observed as the length of the cantilever increases.

Stay 5 Data

The strain data for stay 5 are presented in Figures 30 through 35. In this particular case, it was possible to record strain data from the zero reference level prior to tensioning all the way up to the maximum, including the strain at the maximum pressure prior to fixing the anchors. This peak reading was not available for the previous stays. As may be seen in Figure 30, the increase in average strain as a result of the tensioning, from zero load until the jacks were set, was approximately 2,250 microinches per inch, which compares with values for stay 1 and stay 2 of 2,485 and 2,150 microinches per inch, respectively. However, as may also be seen in the figure, the maximum strain increase during the tensioning process was actually slightly more than 2,800 microinches per inch, which would correspond to a stress during initial tensioning of approximately 92,000 psi, with a tie off stress of approximately 74,000 psi. Although this value is somewhat low relative to the design

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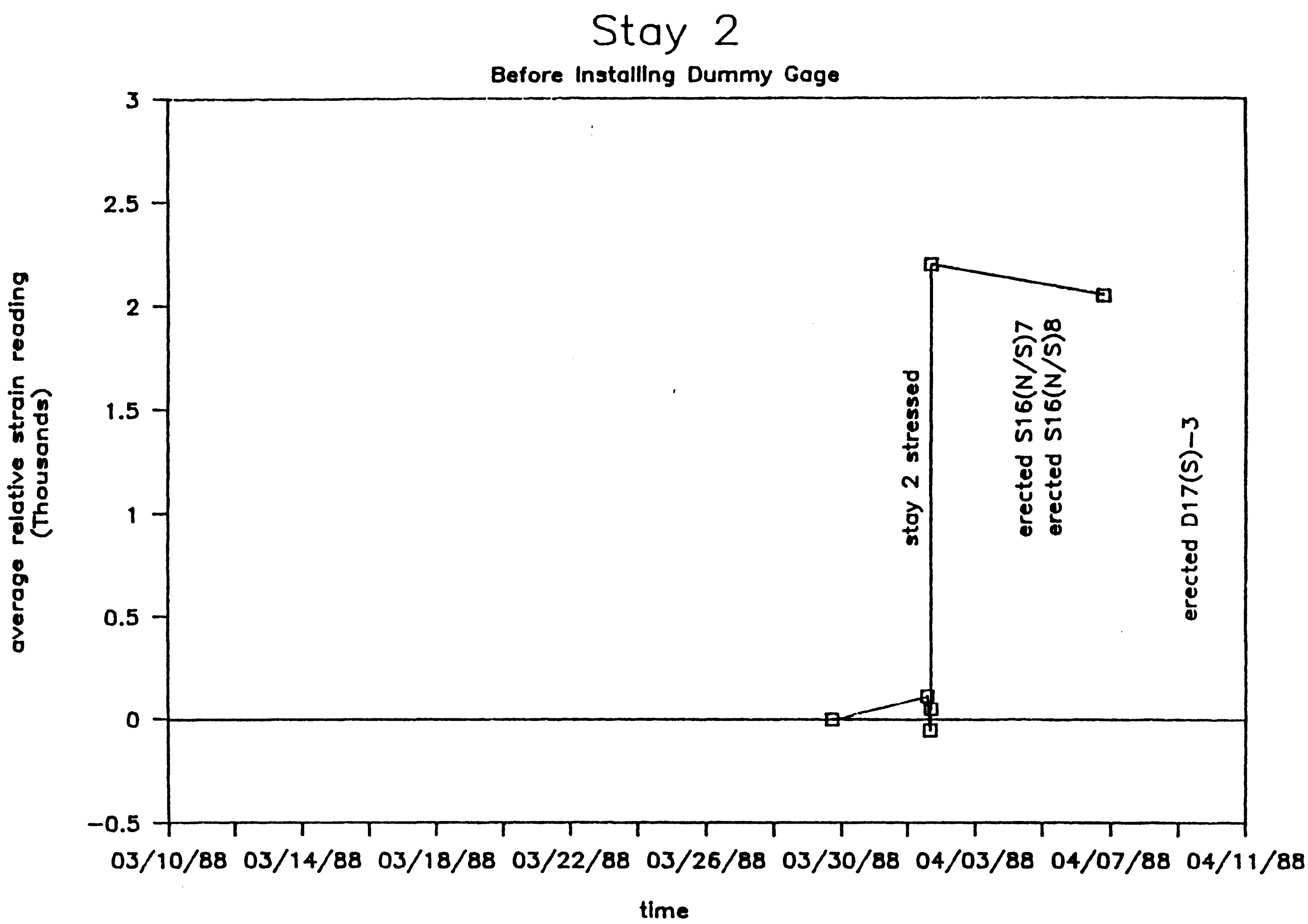

Figure 20. Stay S2, Average Strain Data Before Installation of Dummy Gage

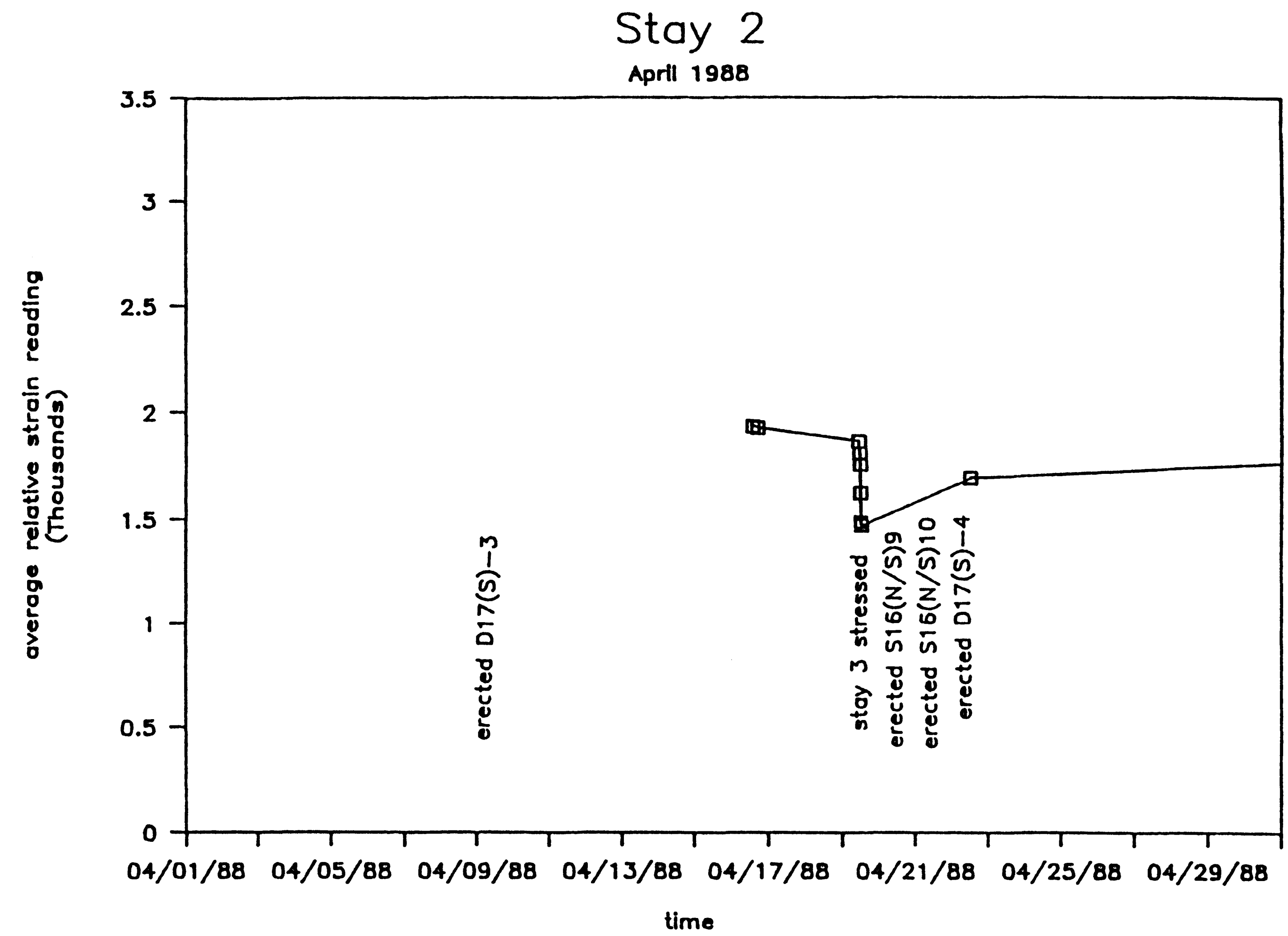

Figure 21. Stay S2, Average Relative Strain Data, April 1988

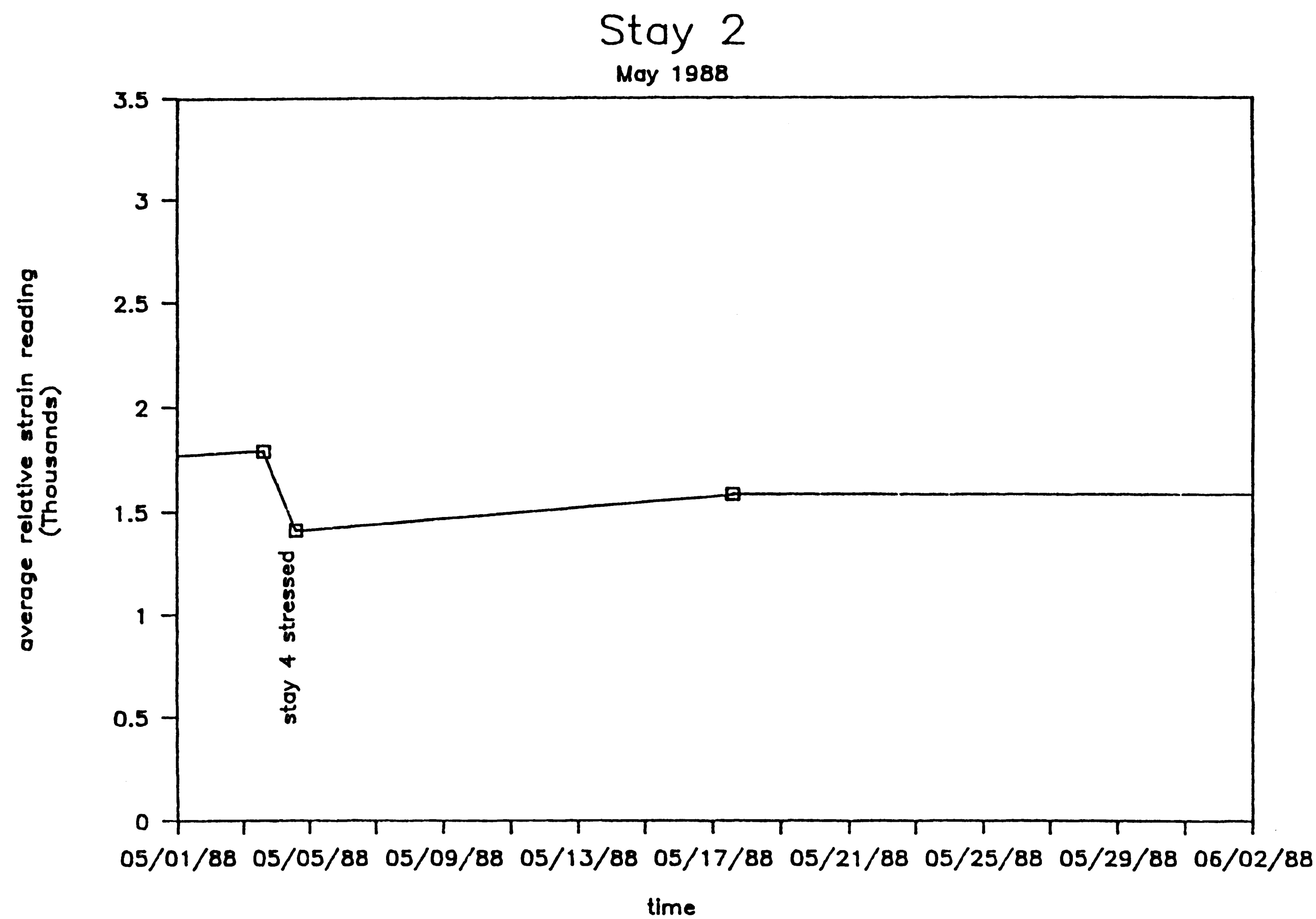

Figure 22. Stay S2, Average Relative Strain Data, May 1988

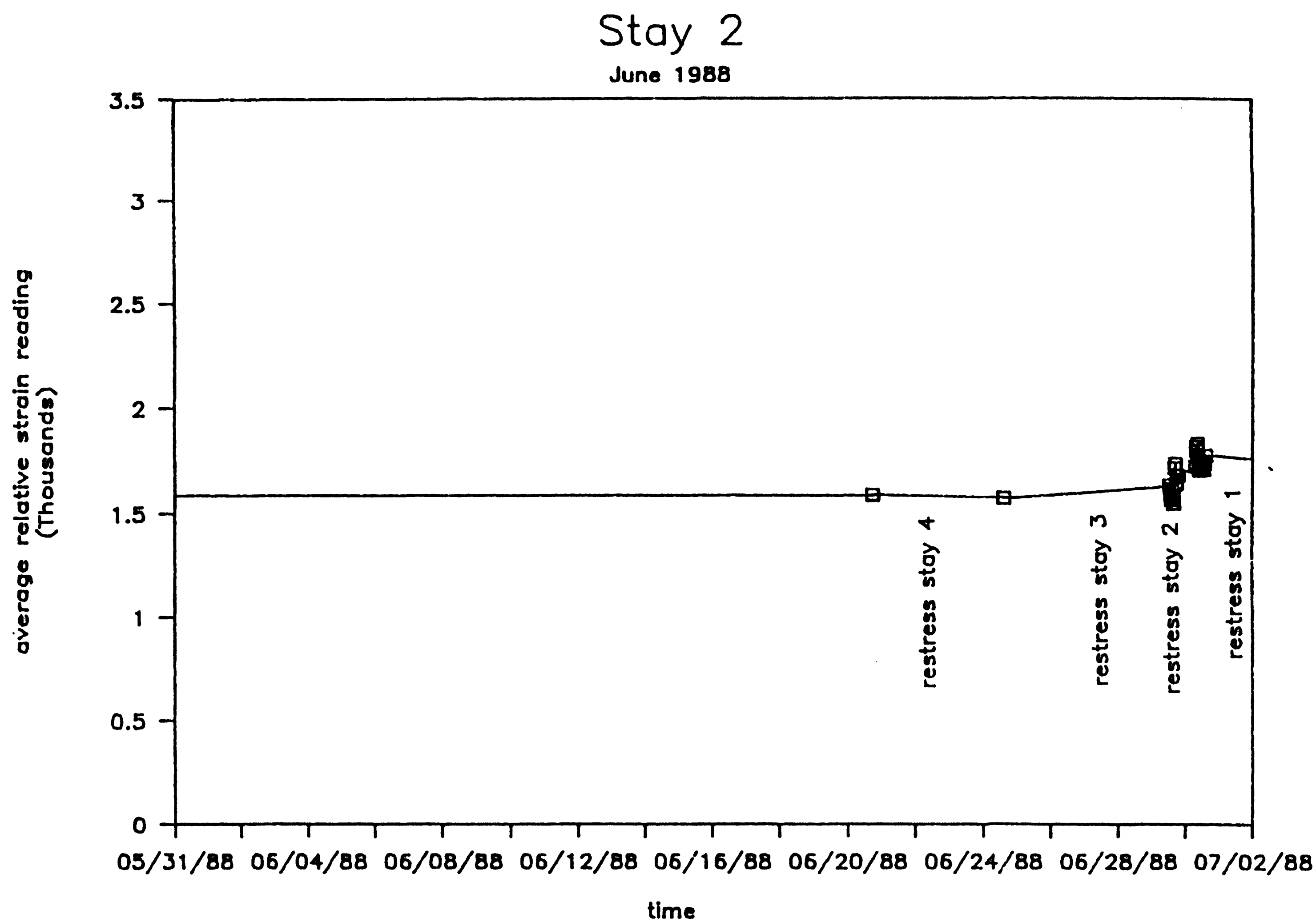

Figure 23. Stay S2, Average Relative Strain Data, June 1988

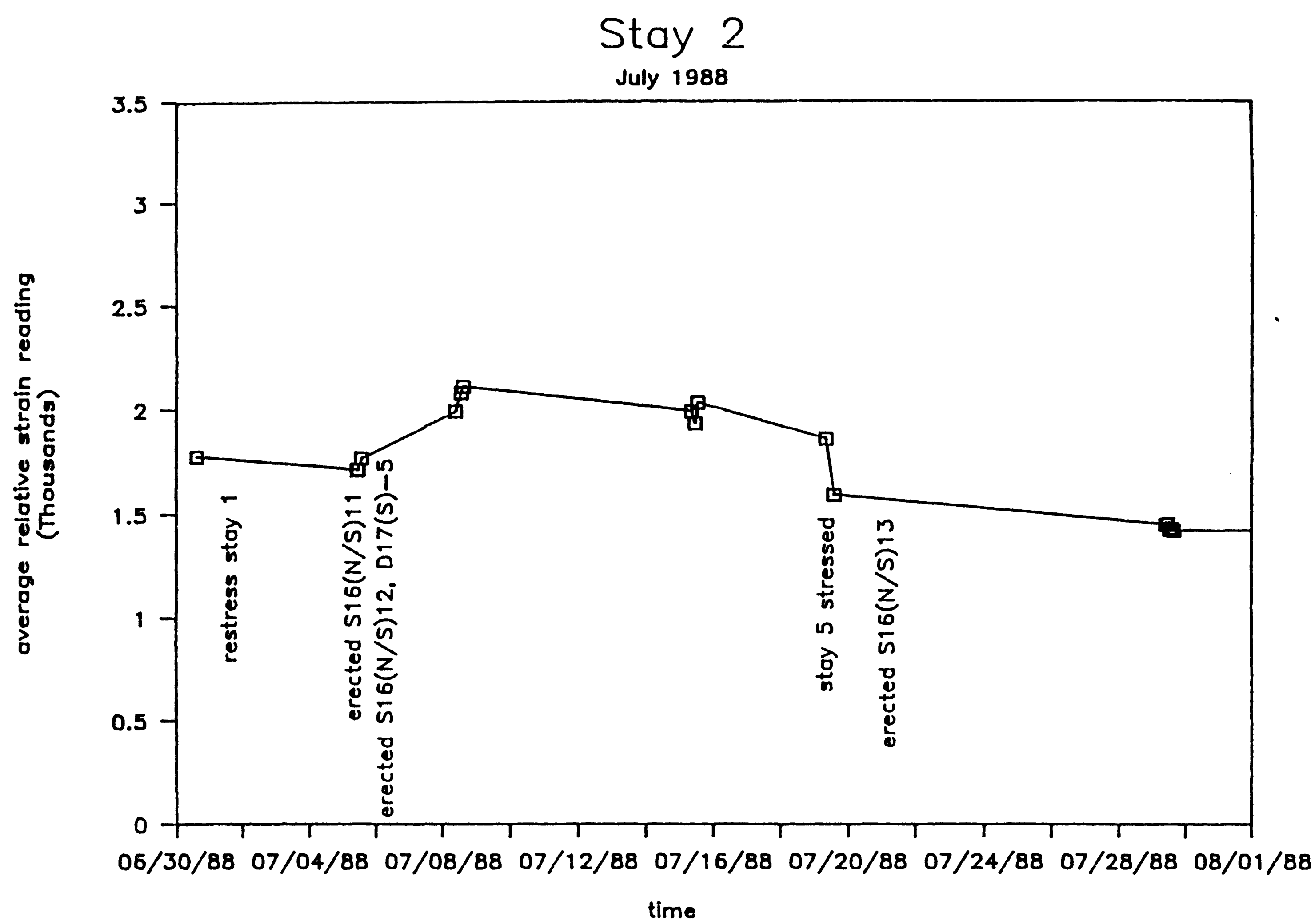

Figure 24. Stay S2, Average Relative Strain Data, July 1988

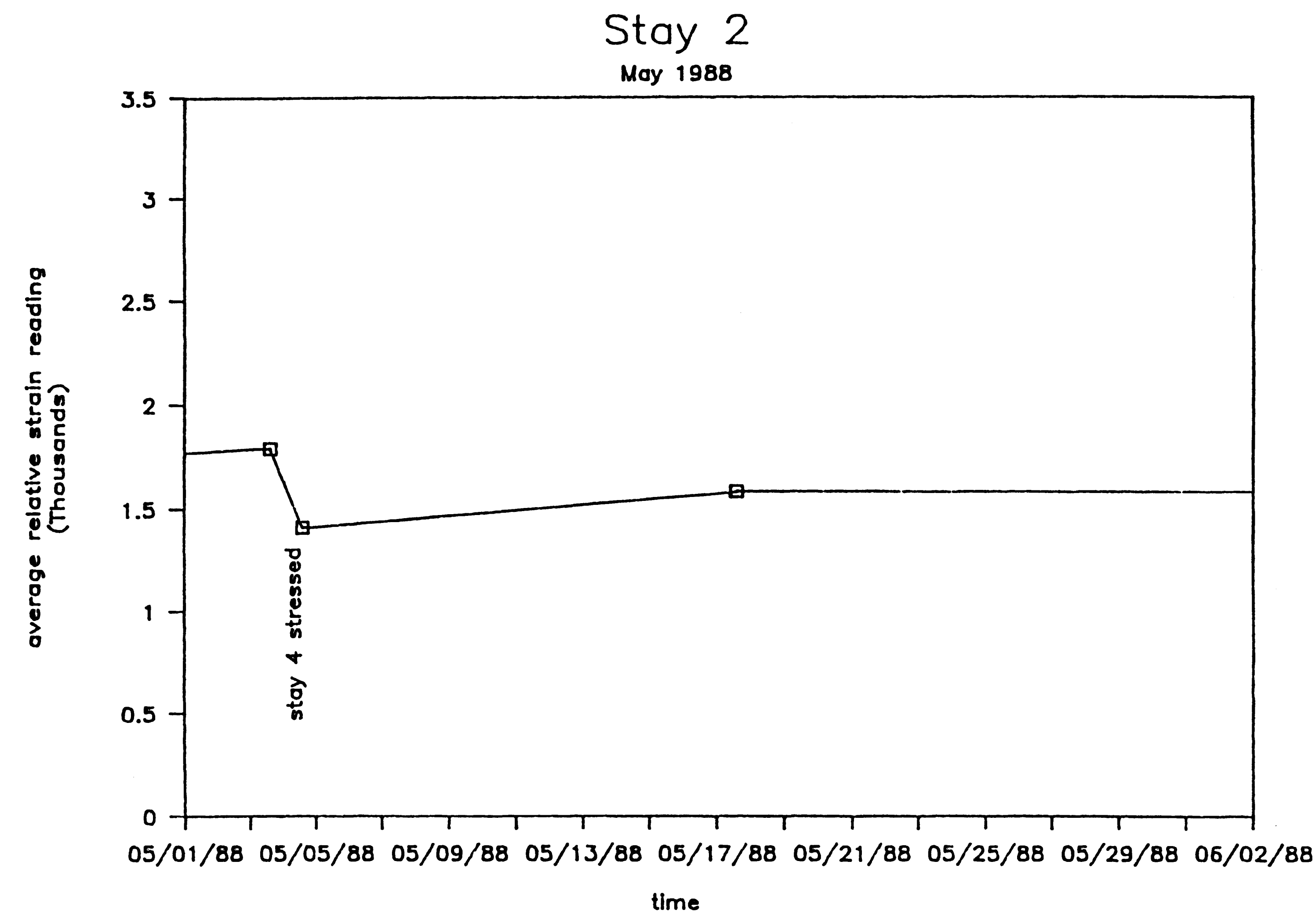

Figure 22. Stay S2, Average Relative Strain Data, May 1988

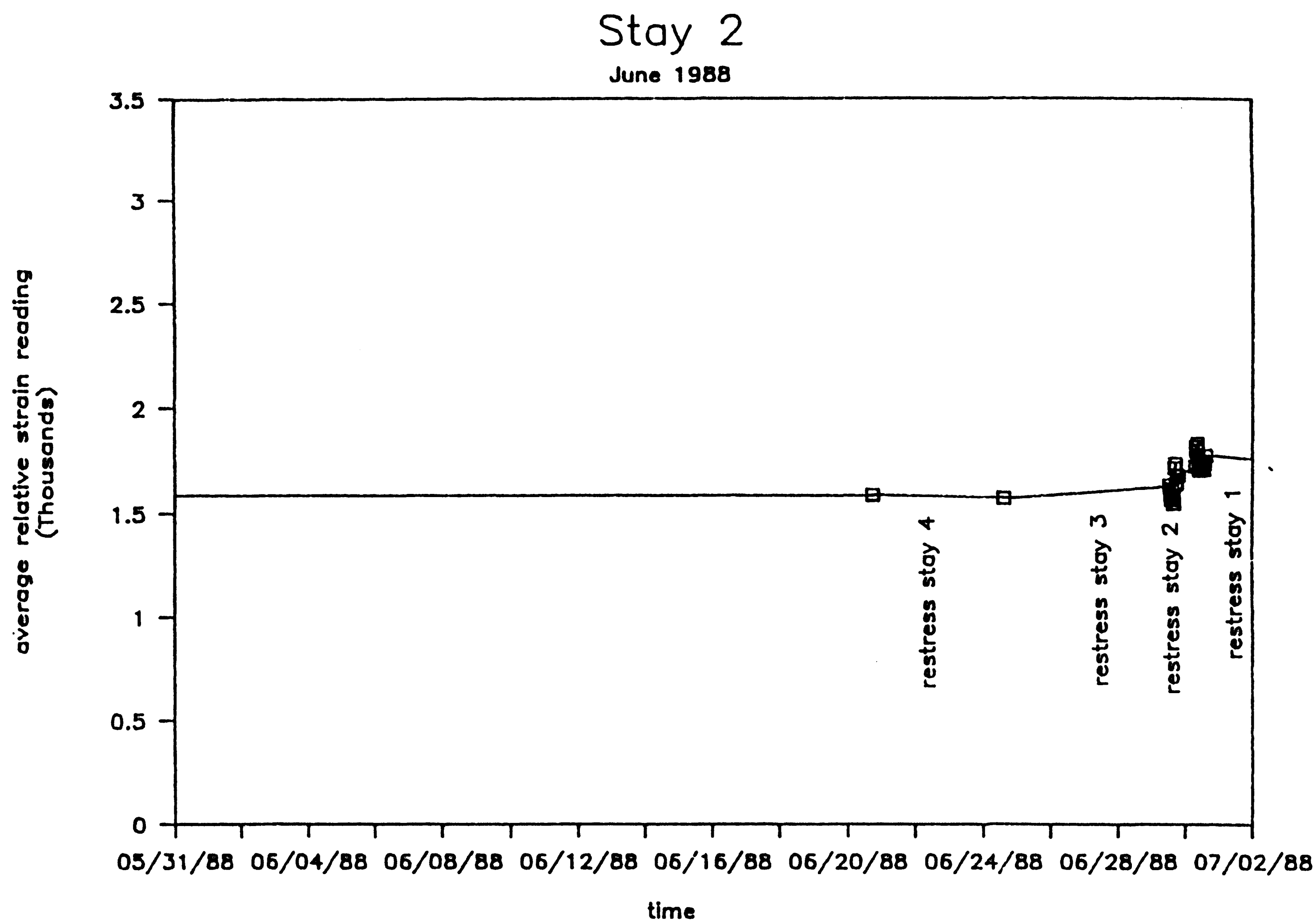

Figure 23. Stay S2, Average Relative Strain Data, June 1988

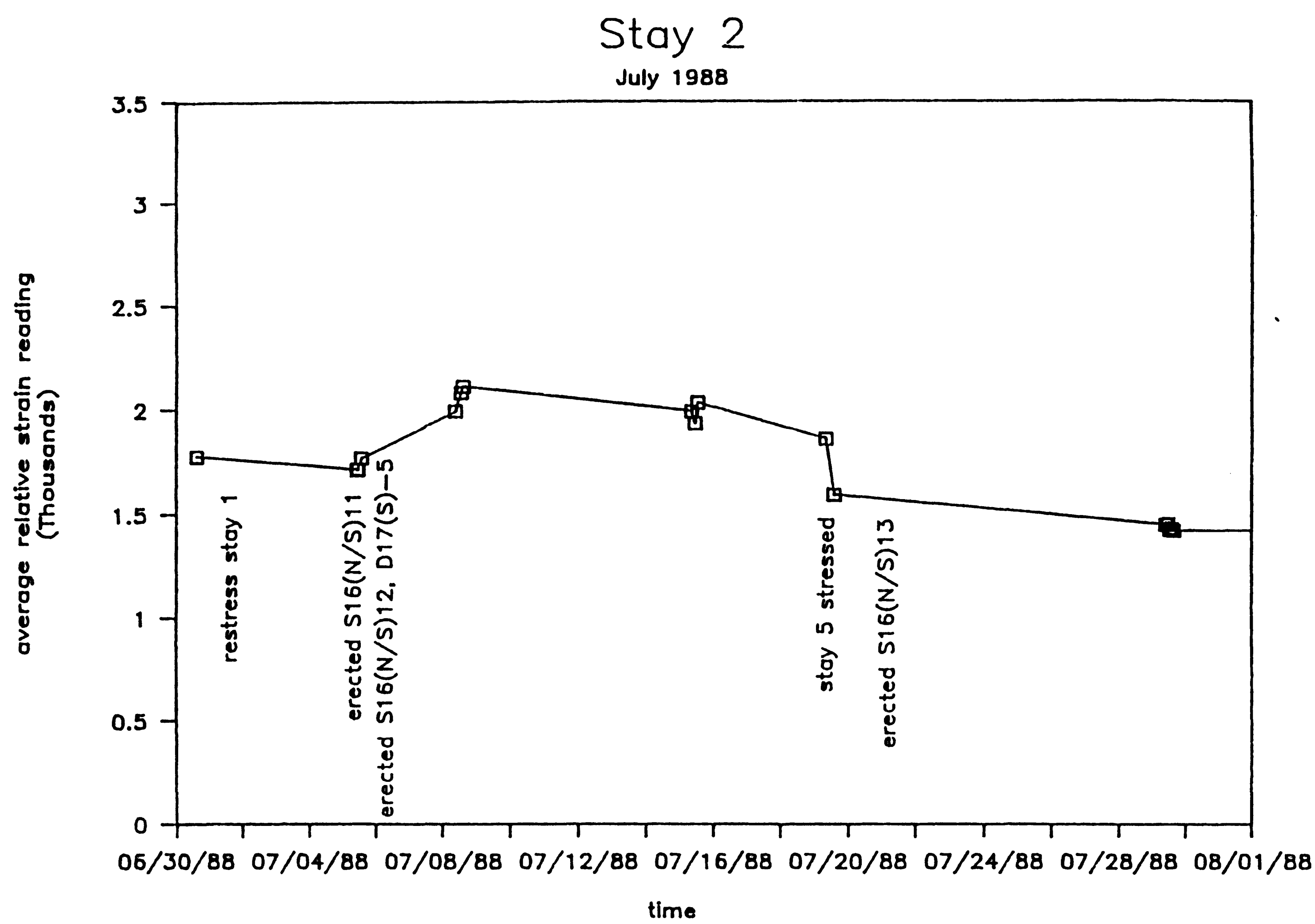

Figure 24. Stay S2, Average Relative Strain Data, July 1988

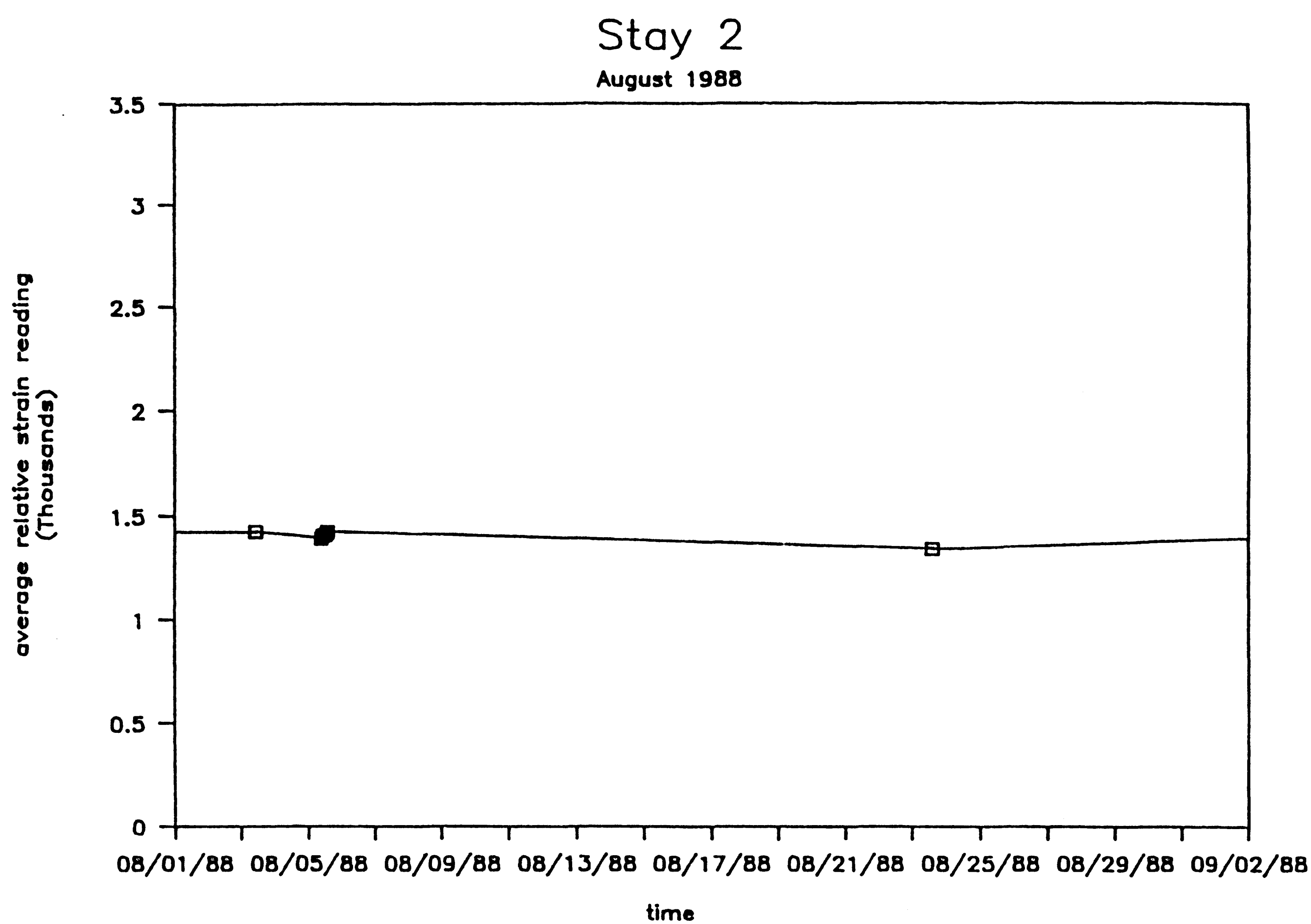

Figure 25. Stay S2, Average Relative Strain Data, August 1988

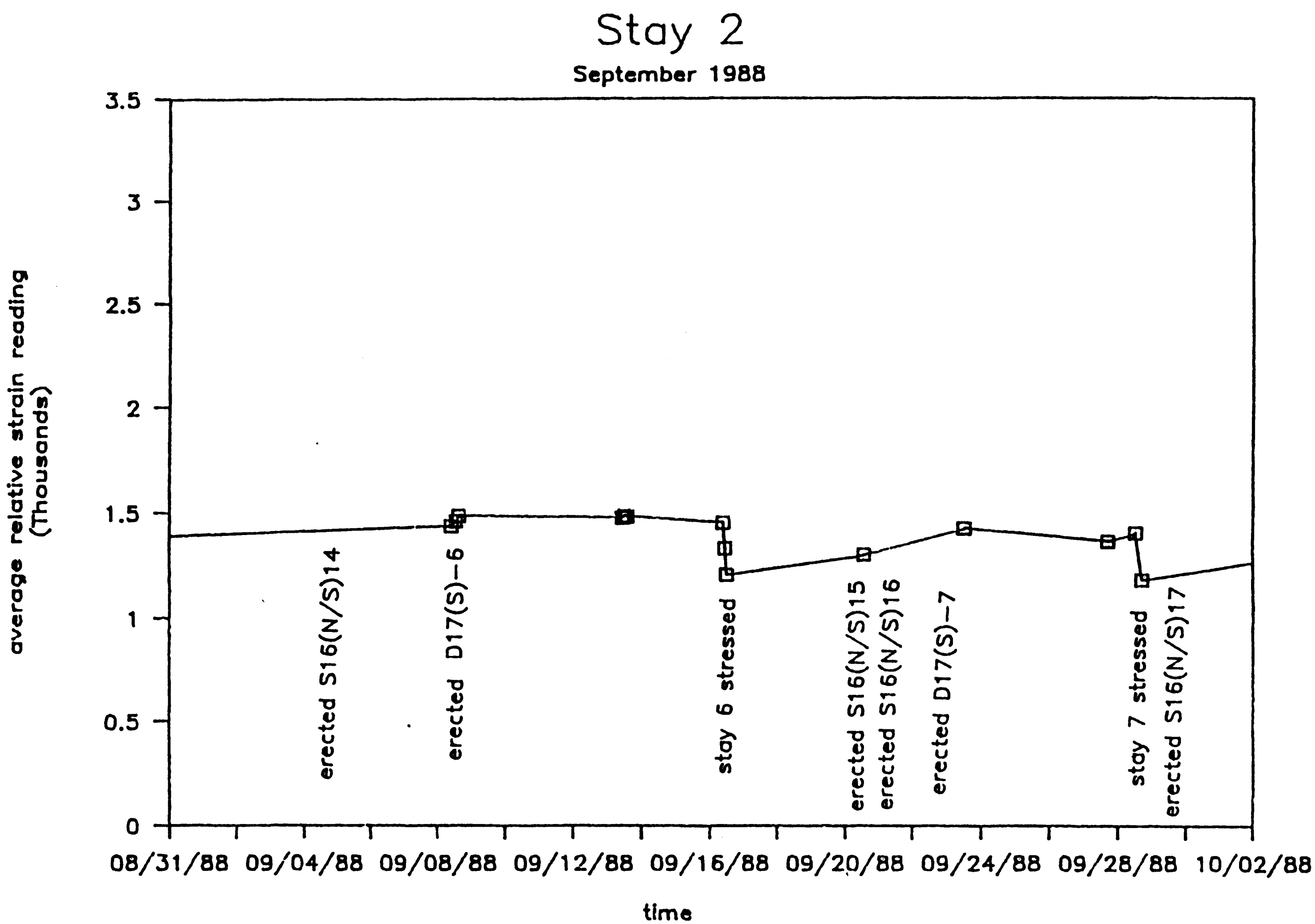

Figure 26. Stay S2, Average Relative Strain Data, September 1988

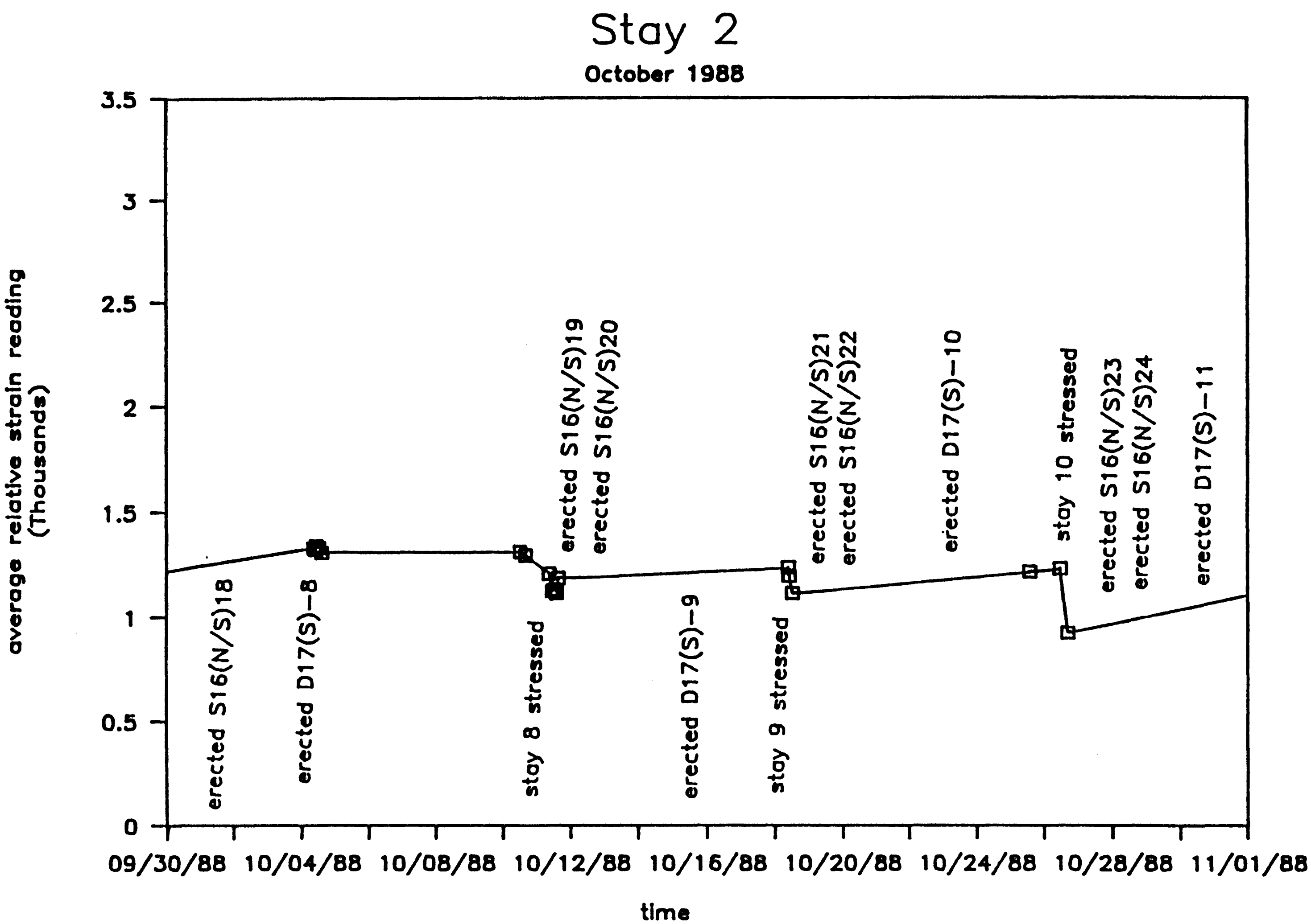

Figure 27. Stay S2, Average Relative Strain Data, October 1988

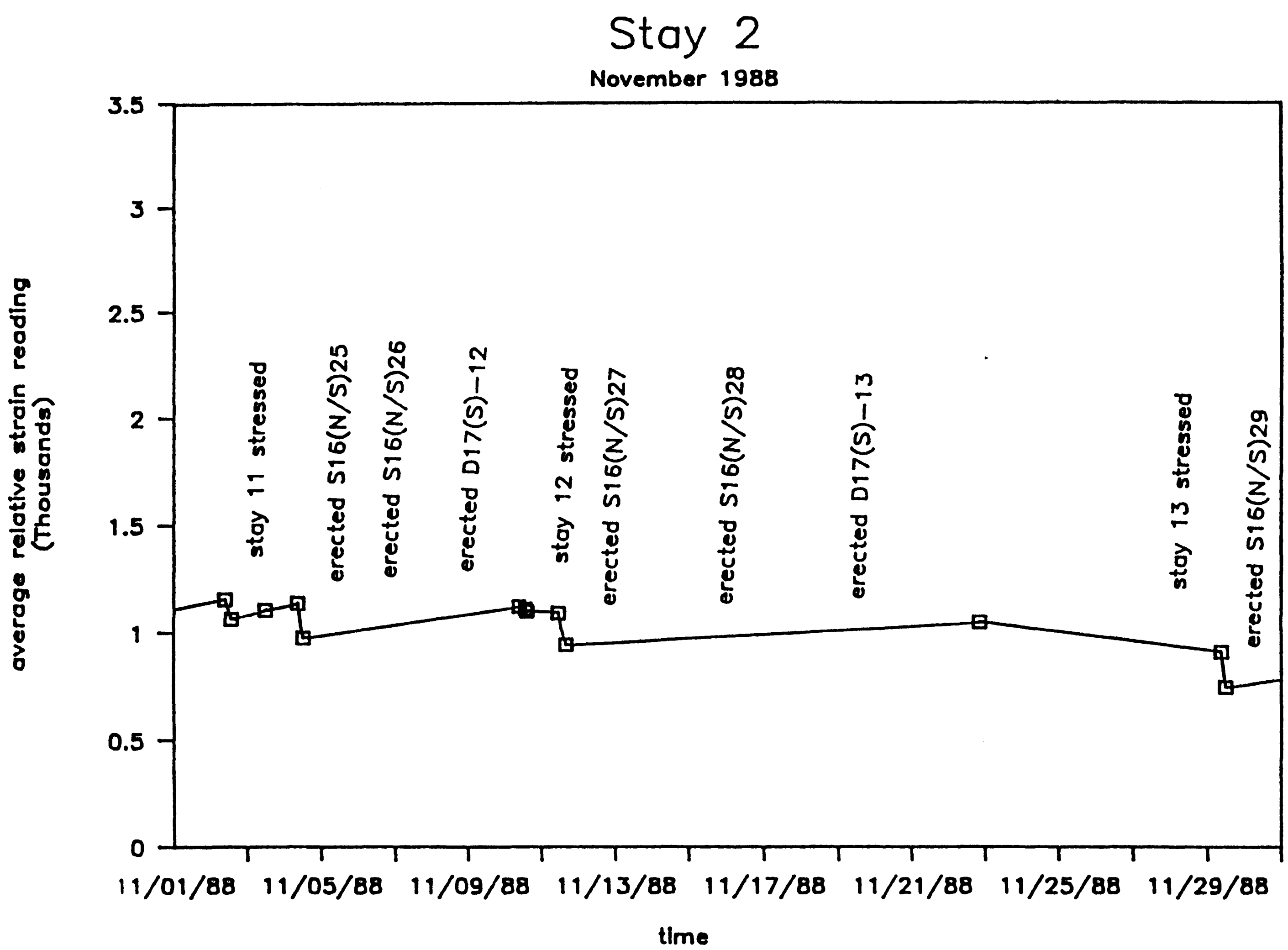

Figure 28. Stay S2, Average Relative Strain Data, November 1988

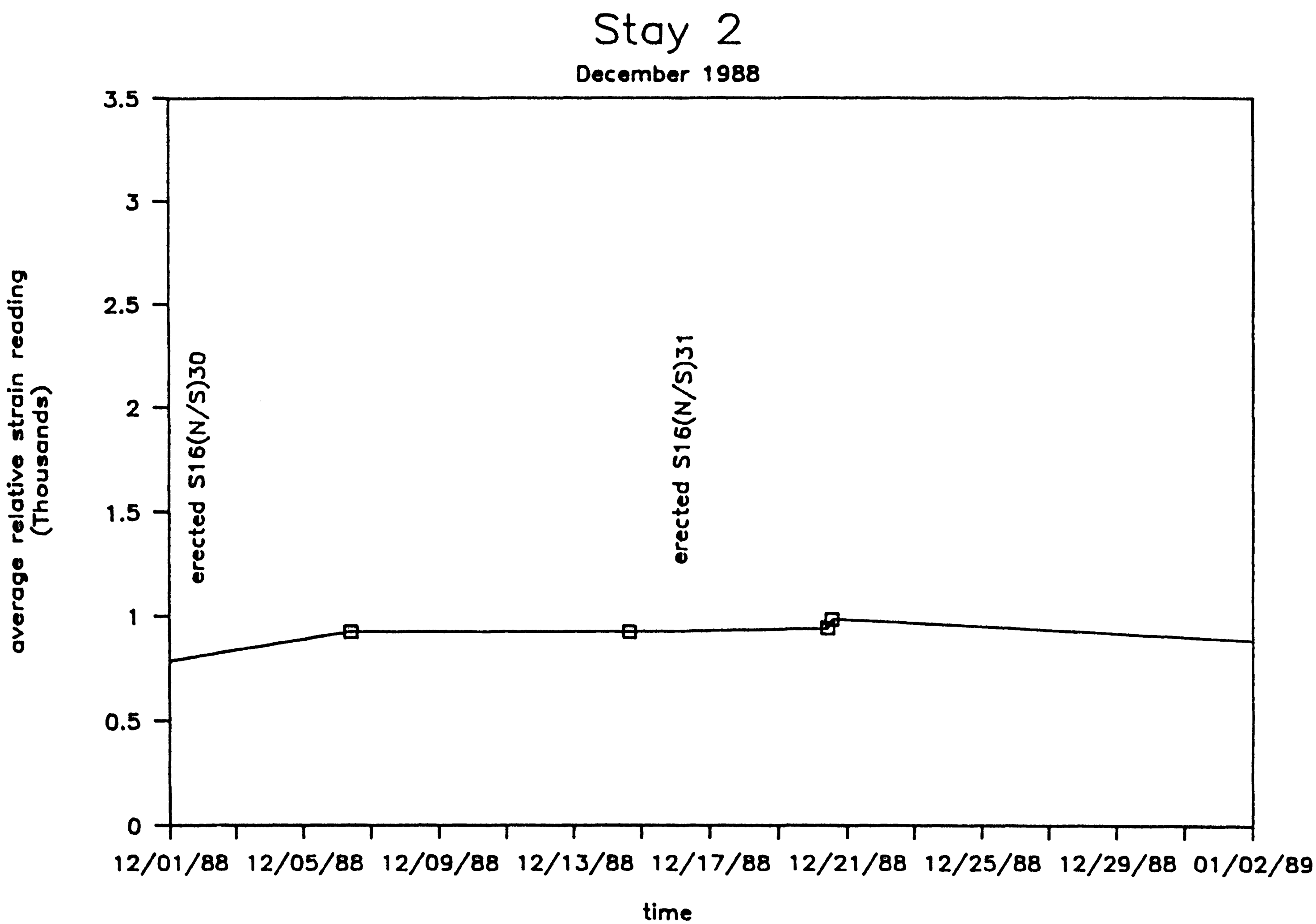

Figure 29. Stay S2, Average Relative Strain Data, December 1988

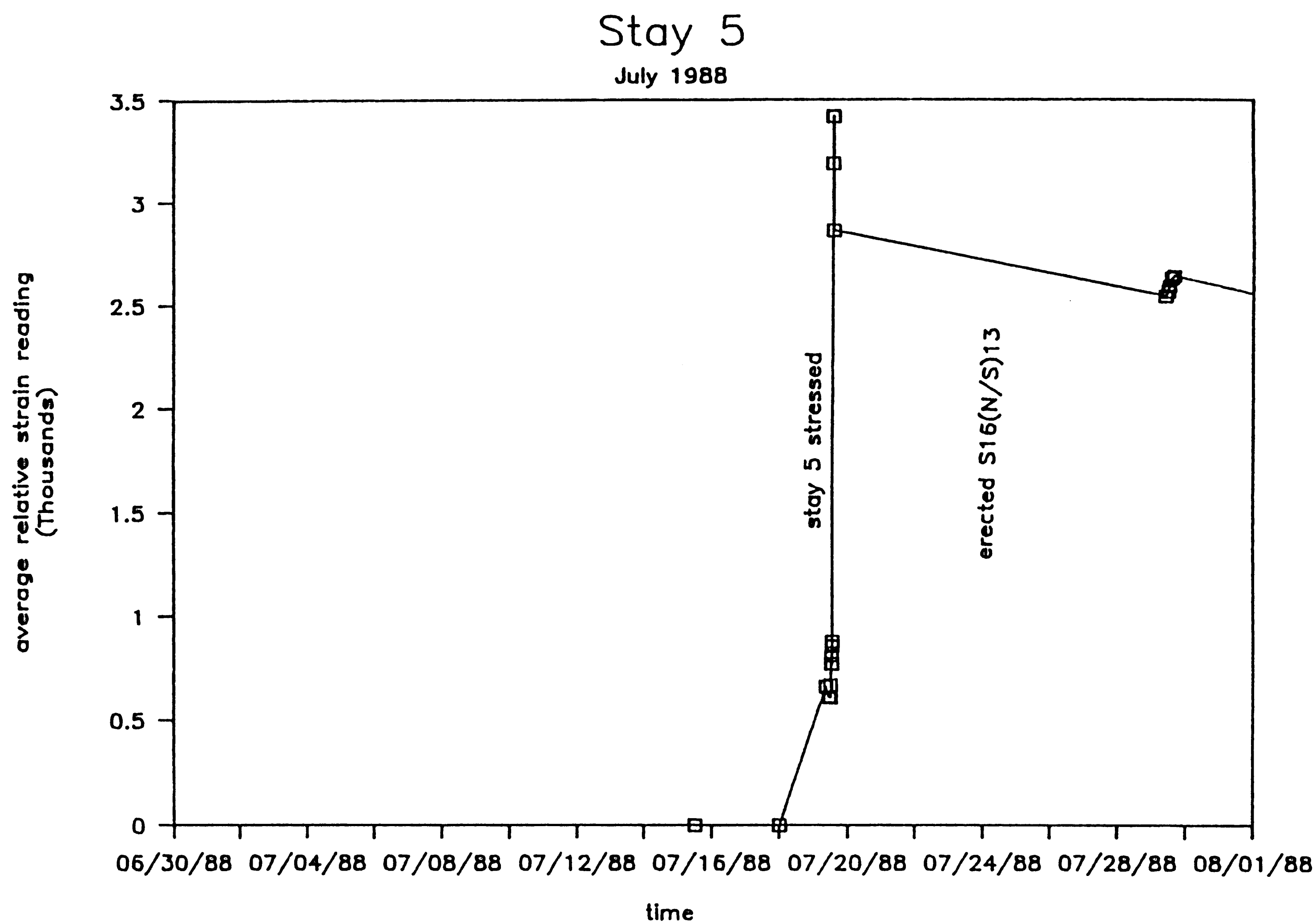

Figure 30. Stay S5, Average Strain Data, July 1988

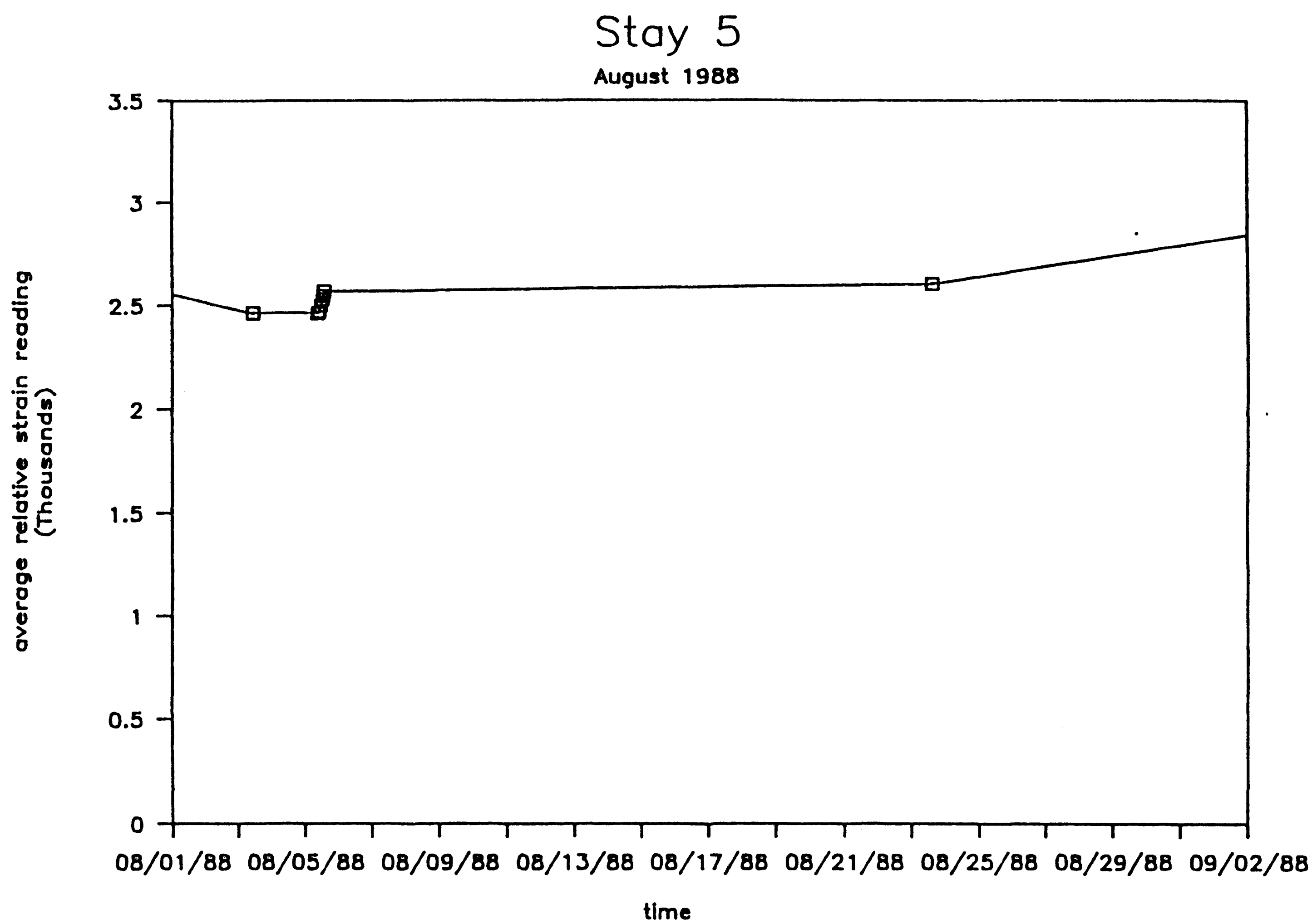

Figure 31. Stay S5, Average Relative Strain Data, August 1988

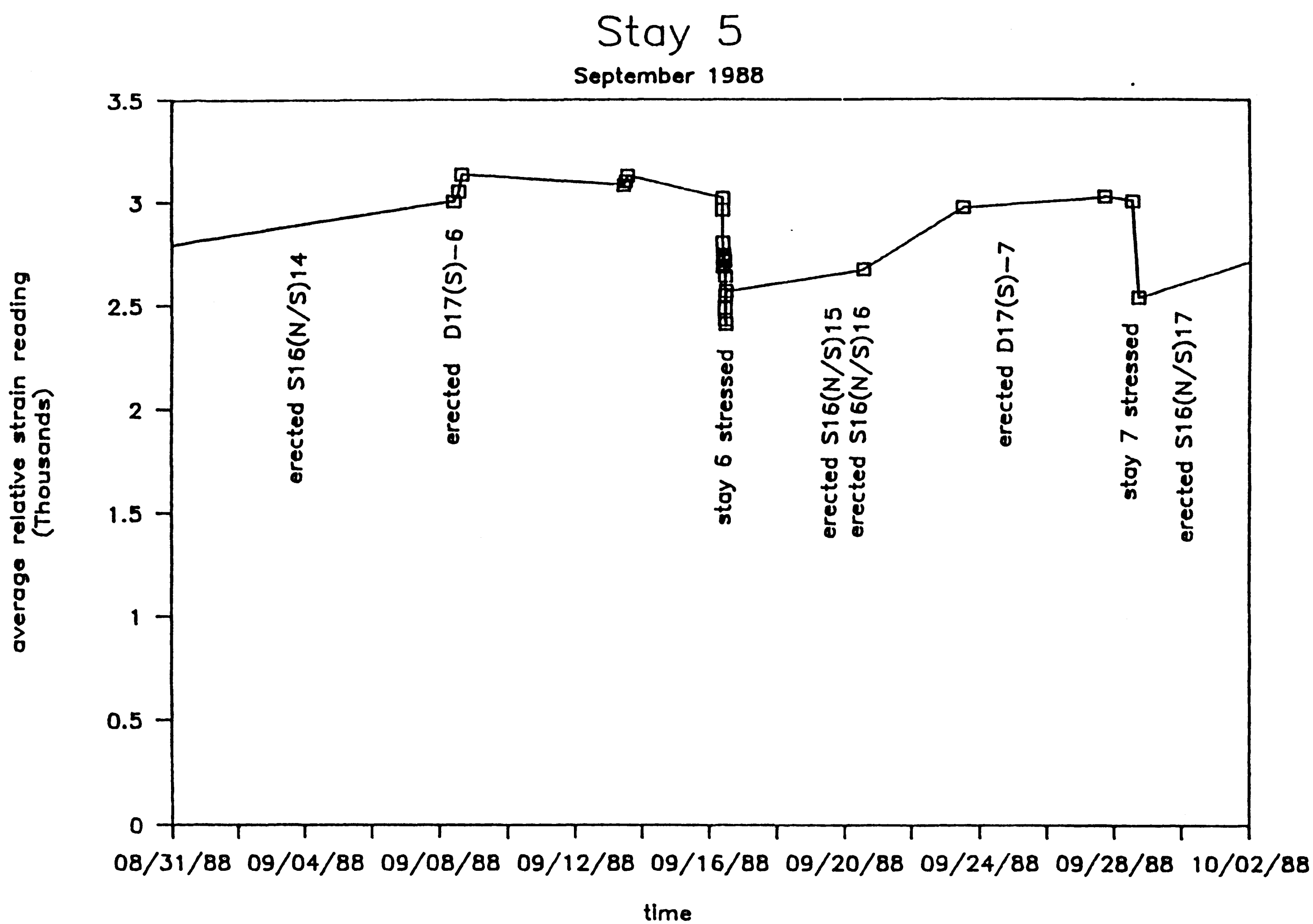

Figure 32. Stay S5, Average Relative Strain Data, September 1988

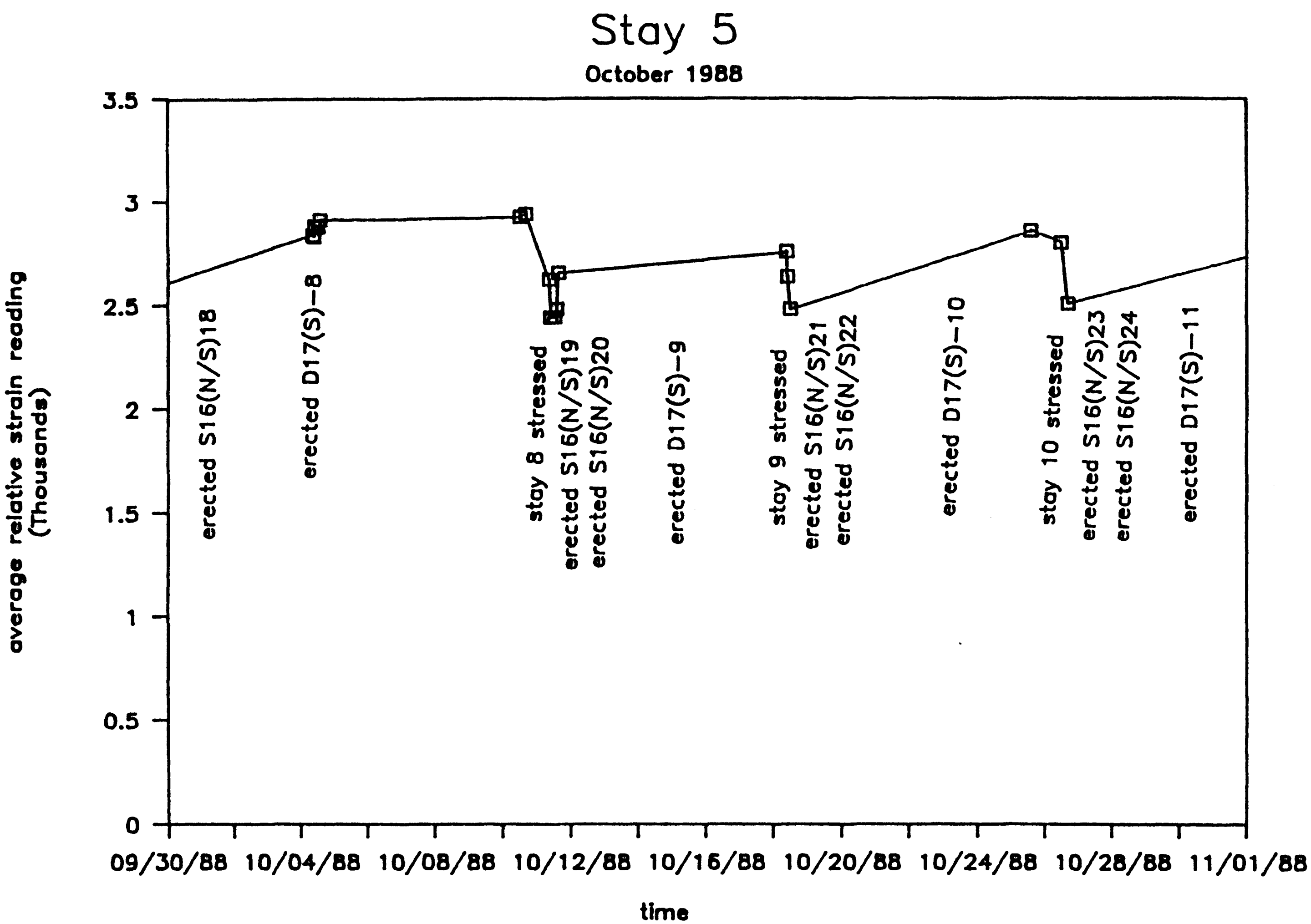

Figure 33. Stay S5, Average Relative Strain Data, October 1988

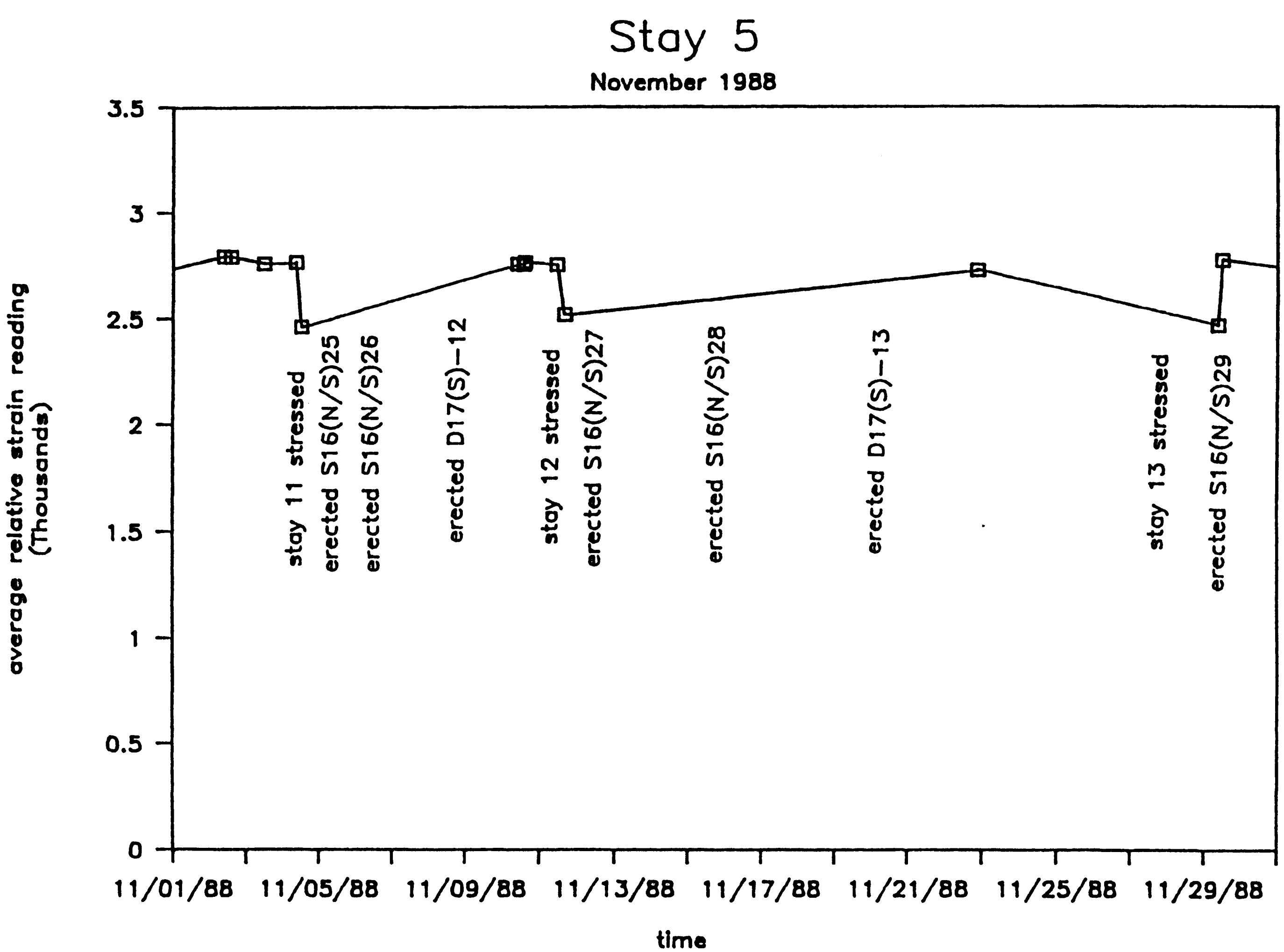

Figure 34. Stay S5, Average Relative Strain Data, November 1988

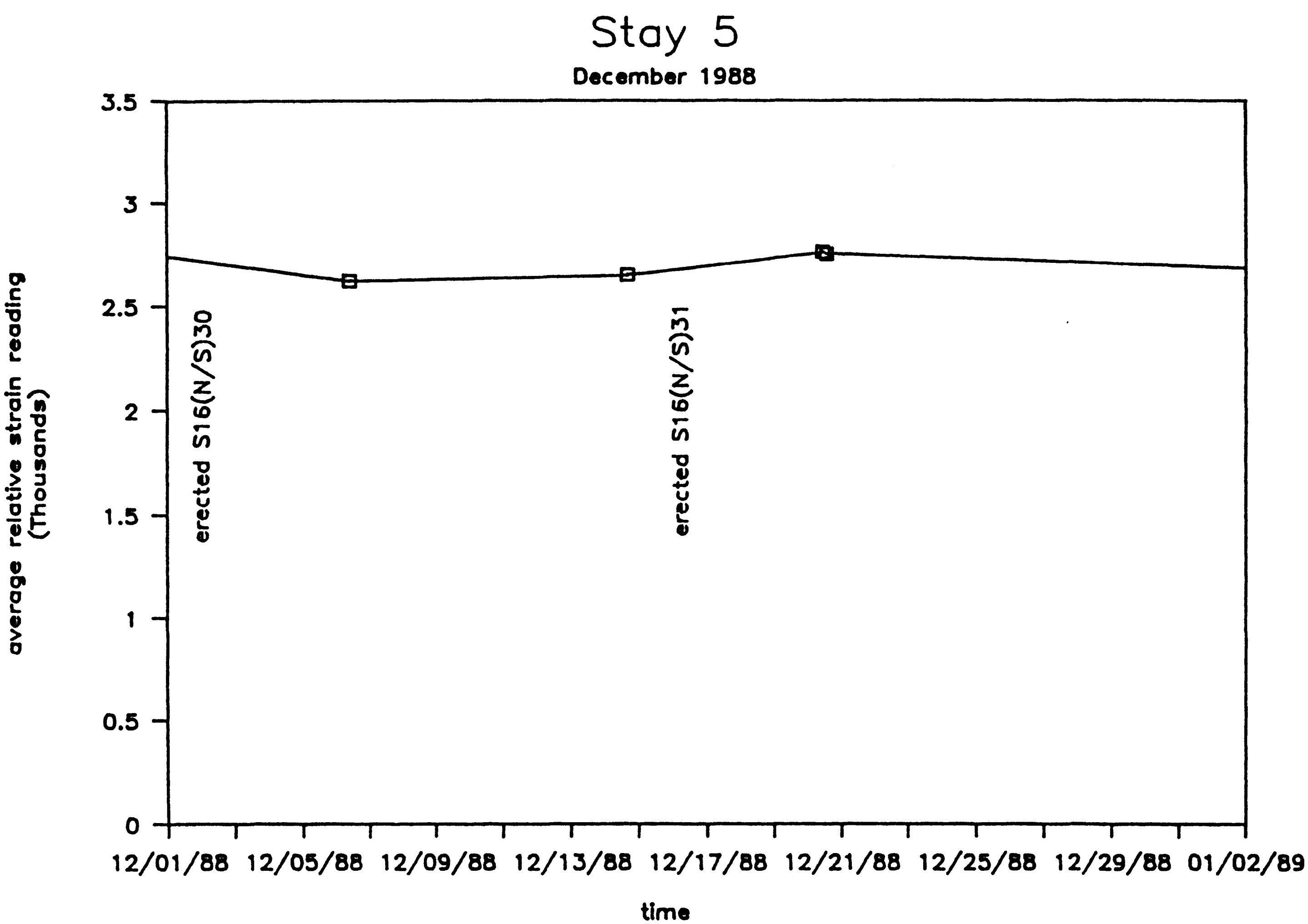

Figure 35. Stay S5, Average Relative Strain Data, December 1988

stress, it is consistent with the relatively high level of strand shifting observed during the tensioning procedure. This point will be discussed further.

As was noted for stays 1 and 2, the tensioning of subsequent stays resulted in a slight reduction in strain in stay 5. However, the erection of additional segments in general produced a slight increase in the average strain in stay 5. This would be expected but was contrary to what was observed for stays 1 and 2. This is not unexpected, as stay 5 is located much further from the pier and temporary post tensioning added at this point did not extend all the way back to the pier. In fact, some temporary post tensioning over the pier was removed prior to the tensioning of stay 5.

The strain record for stay 5 was uninterrupted for the entire erection period, thus permitting the total strain variation during the erection to be estimated. The average reduction in strain measured from the time that stay 5 was tensioned until the north cantilever was complete was found to be only approximately 200 microinches per inch. As with the earlier stays, the strain readings were reasonably uniform over the entire construction period, indicating no unusual or unexpected loads occurring in the stays.

Stay 7 Data

Average relative strain readings in stay 7 as a function of time are shown plotted in Figures 36 through 39. In this particular stay, there was some uncertainty in the initial zero reading but it was possible to determine that the average increase in strain in the instrumented wires as a result of tensioning the stay was approximately 2,300 microinches per inch. The maximum increase in average strain during the tensioning process just prior to setting the anchors was approximately 3,100 microinches per inch, which was a somewhat larger increase that was observed for stay 5.

One month after installation of the gages on stay 7 and tensioning of the stay, there was a discontinuity in the strain data as a result of the failure of the dummy gage during the tensioning of stay 9. A replacement dummy gage was installed, and subsequent strain data should be consistent with that recorded earlier before the failure, but there is always the possibility of a slight shift.

In stay 5 it was noted that the erection of additional segments beyond the stay caused modest increases in the average strain in the stay, whereas slight reductions in average strain were observed for stays 1 and 2 when additional segments were added. From Figures 36 through 39, it is obvious that the addition of segments beyond stay 7 produced significant increases in average strain in stay 7. For example, the erection of the next two deck segments and the delta frame, just prior to the installation of stay 8, resulted in a strain increase in stay 7 of almost 2,400 microinches per inch, a much more pronounced effect than observed with previous stays. A similar but smaller increase occurred in stay 7 with the erection of the next two segments, but the erection of segments beyond stay 9 appeared to have

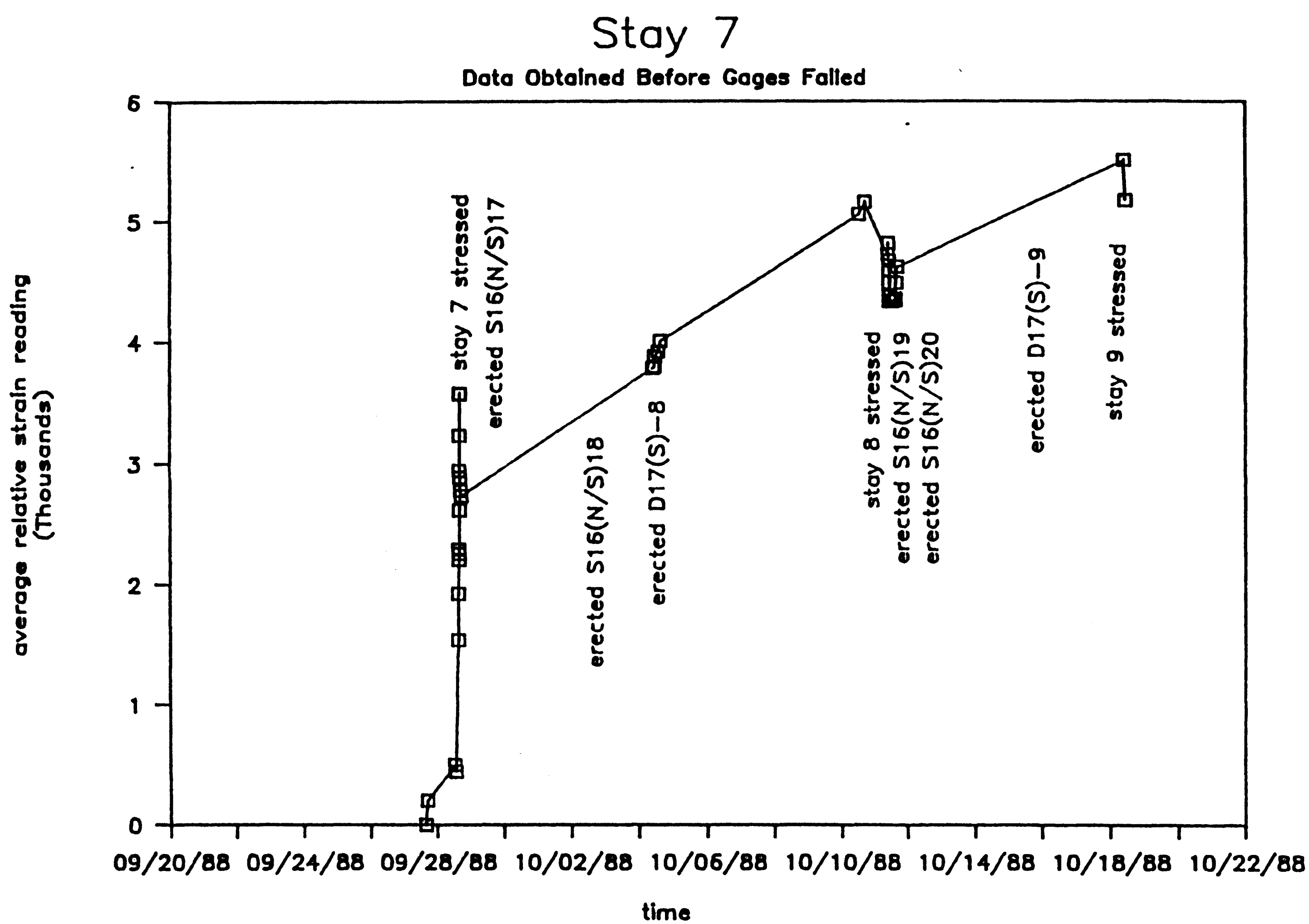

Figure 36. Stay S7, Average Strain Data Obtained Before Gages Failed

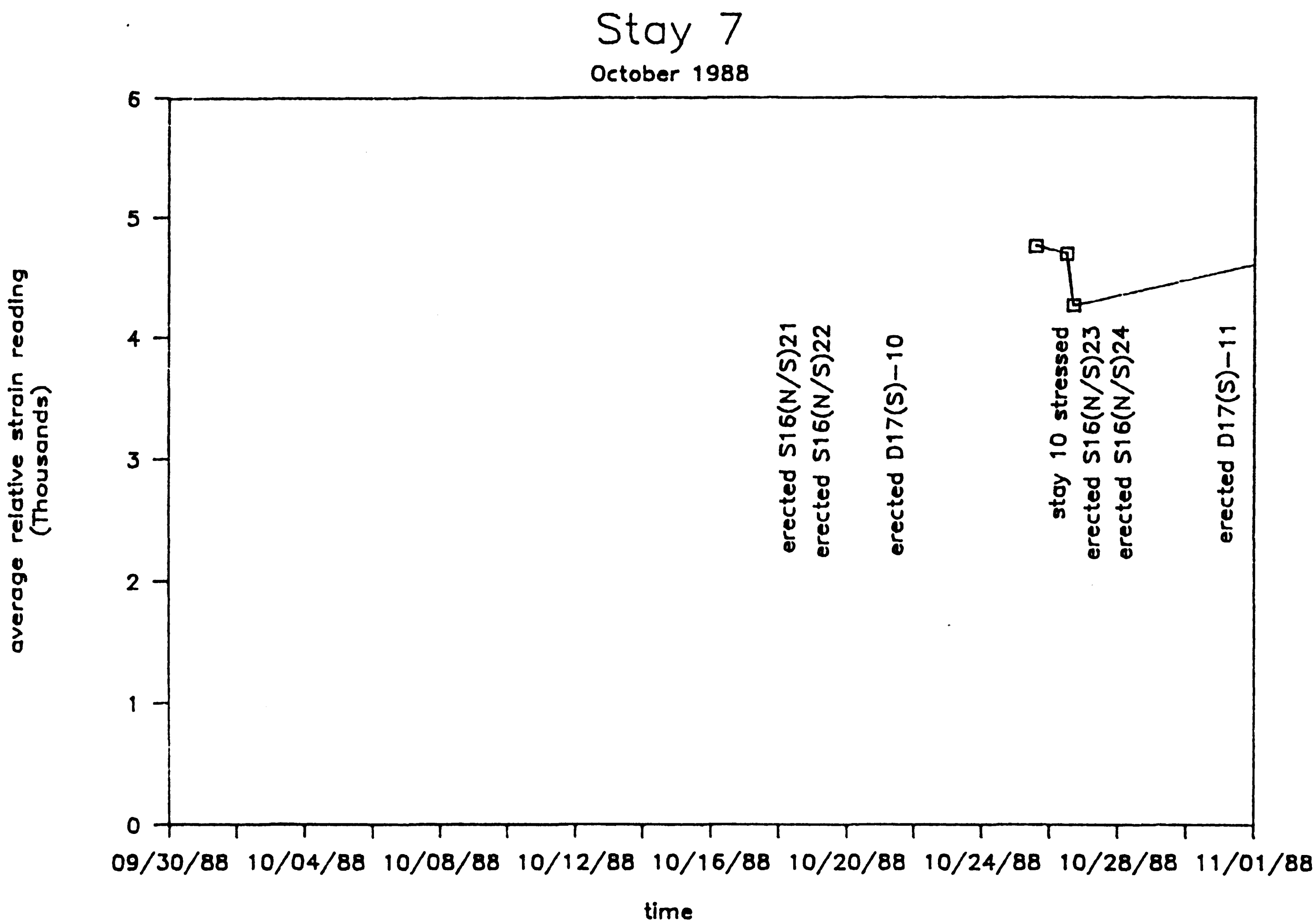

Figure 37. Stay S7, Average Relative Strain Data, October 1988

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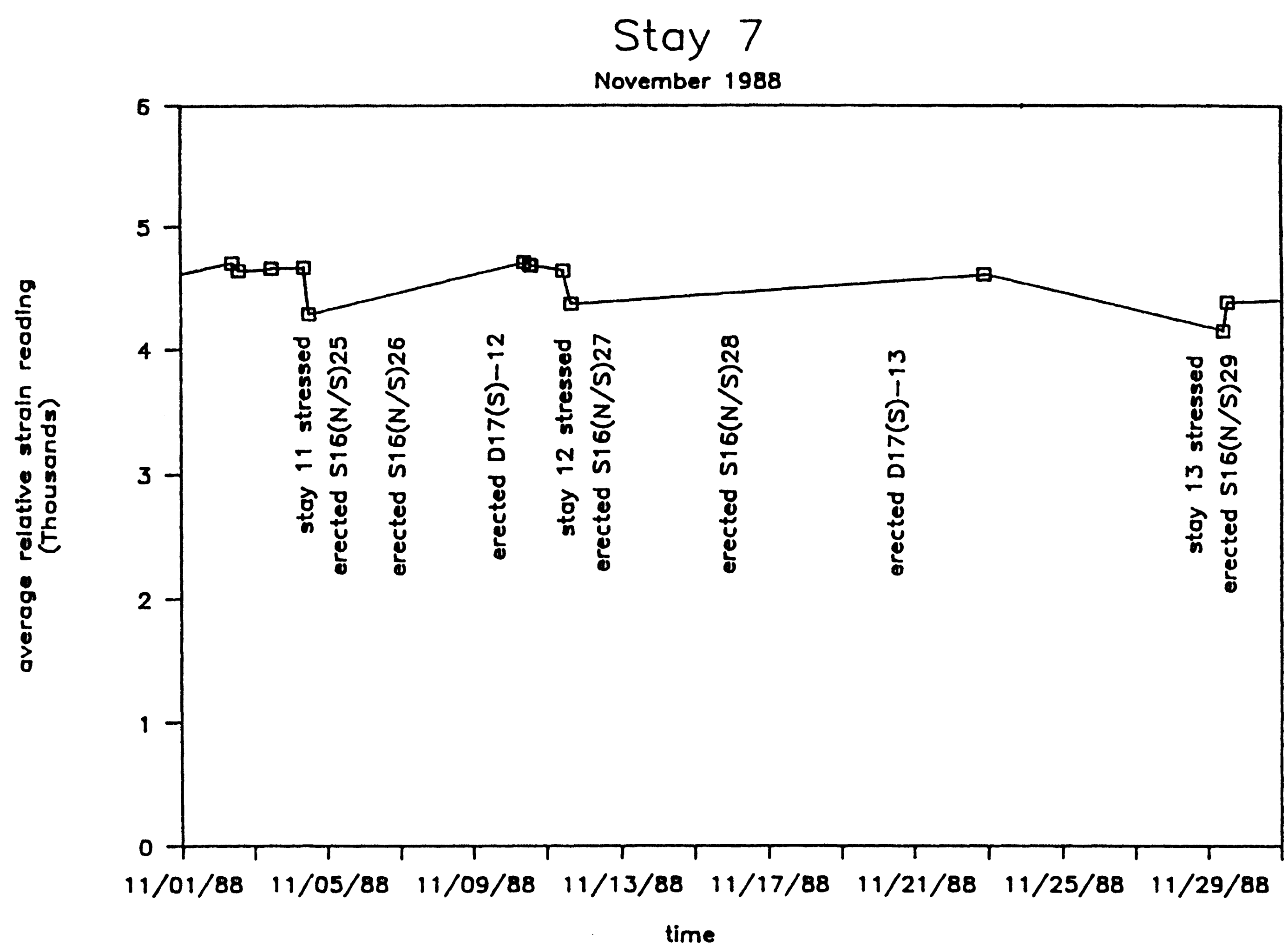

Figure 38. Stay S7, Average Relative Strain Data, November 1988

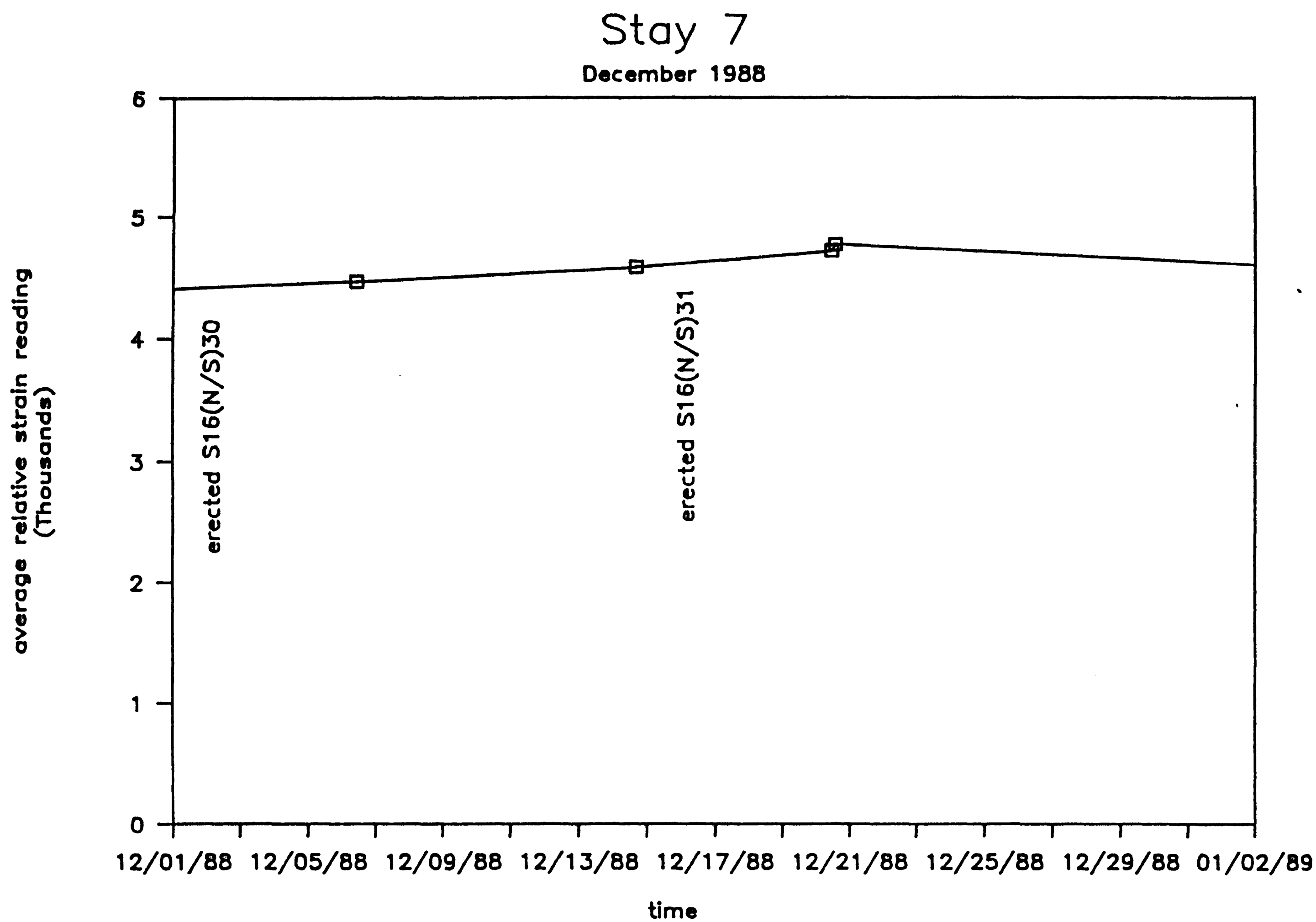

Figure 39. Stay S7, Average Relative Strain Data, December 1988

no effect on the average strain in stay 7. These readings were taken during the 3-week period preceding the failure of the dummy gage, so it may well be that the large strain changes observed during this period may be attributable to drift of the dummy gage, leading to failure.

Examination of the strain data for stay 7 indicated that the tensioning of subsequent stay cables always produced a slight reduction in the average strain in stay 7. This observed behavior is identical with that noted with all previous stays. However, it is also noted from the data plotted in the figures that, unlike earlier stay cables, the subsequent construction activities associated with additional stays and additional segments resulted in a net increase in the average strain in stay 7 of approximately 2,000 microinches per inch, whereas previously instrumented stays showed a net reduction in average strain from tensioning to completion of the cantilever. If the large changes in average strain that occurred preceding the dummy gage failure are discounted, there was a net decrease in gage strain of roughly 500 microinches per inch subsequent to the installation of stay 9, which is much more consistent with the remaining data.

Stay 13 Data

Stay 13 was the last stay cable in the north cantilever, and thus the strain data from this stay are limited. The average relative strain data for stay 13 are shown in Figure 40 for the month of December 1988. Because of the construction scheduling and operation, it was not possible to install the gages prior to stay tensioning and, hence, no data are available relating to the increase in average strain during the tensioning process. However, the limited data available do indicate that the gages are operational, and useful data should be recorded in the future.

Individual Strand Data

The strain data presented thus far for the five instrumented stay cables have been in the form of average relative strains. It is of considerable interest to examine the range of strains observed during similar construction activities in a single stay. Nominally, it would appear that the strain changes should all be virtually identical. It was decided to conduct a more detailed analysis of the strain data for the individual strands of stay 5 since the instrumentation on this stay was more reliable and was associated with fewer problems than with other stays.

The strain data recorded from the four gages on the individual strands of stay 5 are presented in Figures 41 through 47. At the time the stay was tensioned, it was apparent that there was considerable variability in the strains measured in the different strands. In fact, the range of readings during tensioning was so large that the investigators questioned initially whether all of the gages were functioning properly. Once the initial tensioning had been applied, however, the individual strands behaved in the same manner, as evidenced by the almost identical strain increments recorded for the different strands. The technician taking the readings

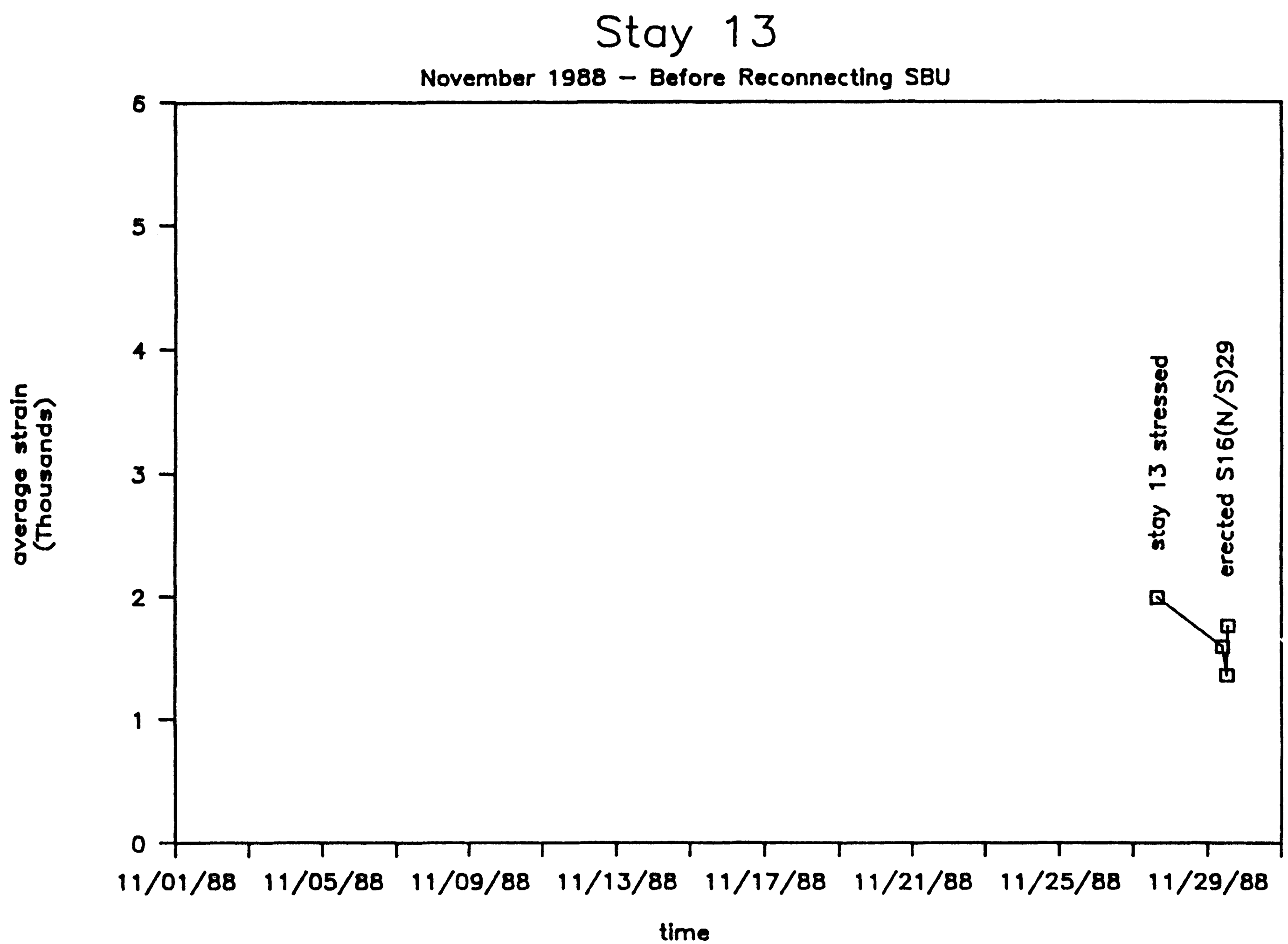

Figure 40. Stay S13, Average Strain Data Obtained Before Reconnecting Switch and Balance Unit

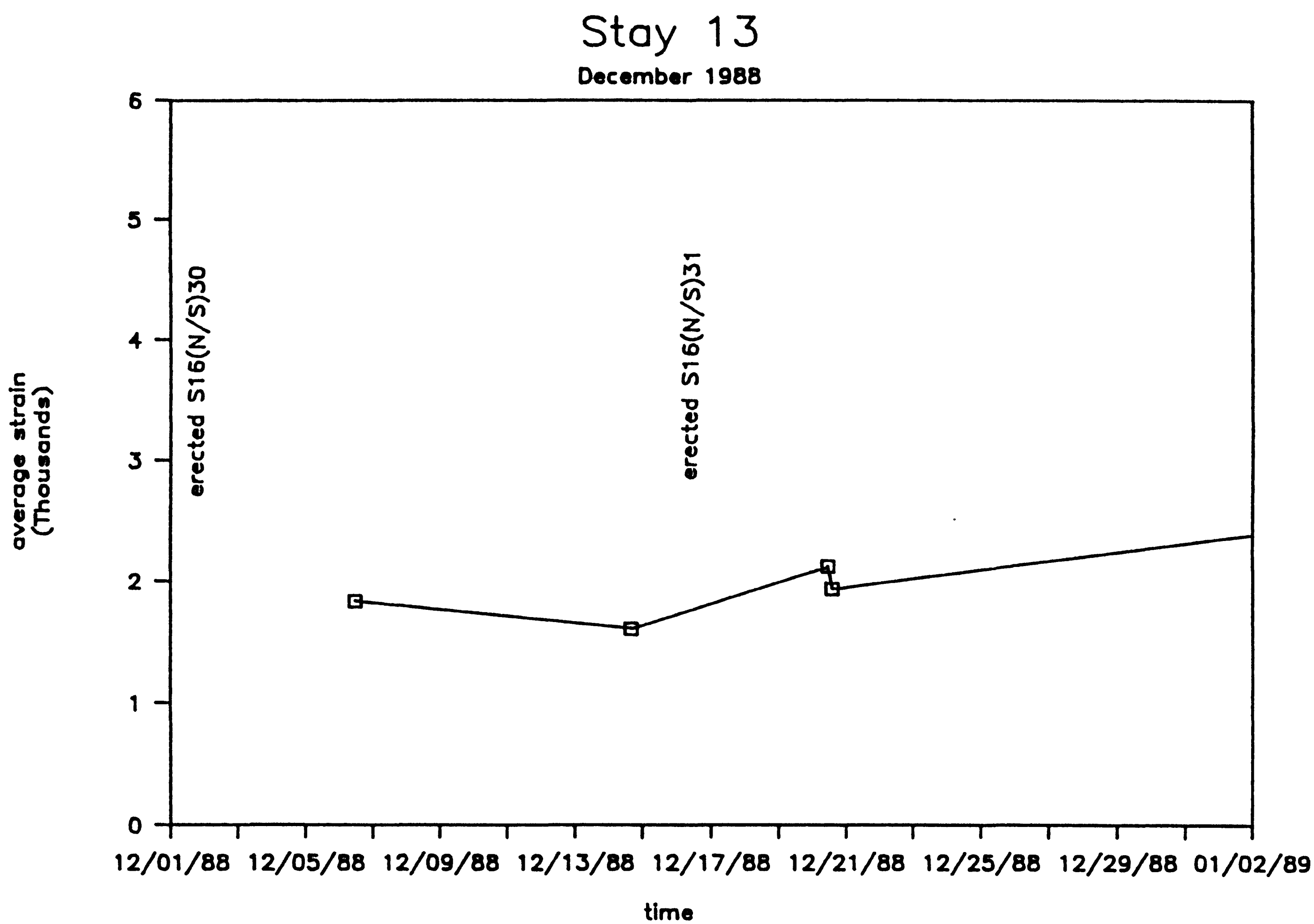

Figure 41. Stay S13, Average Strain Data, December 1988

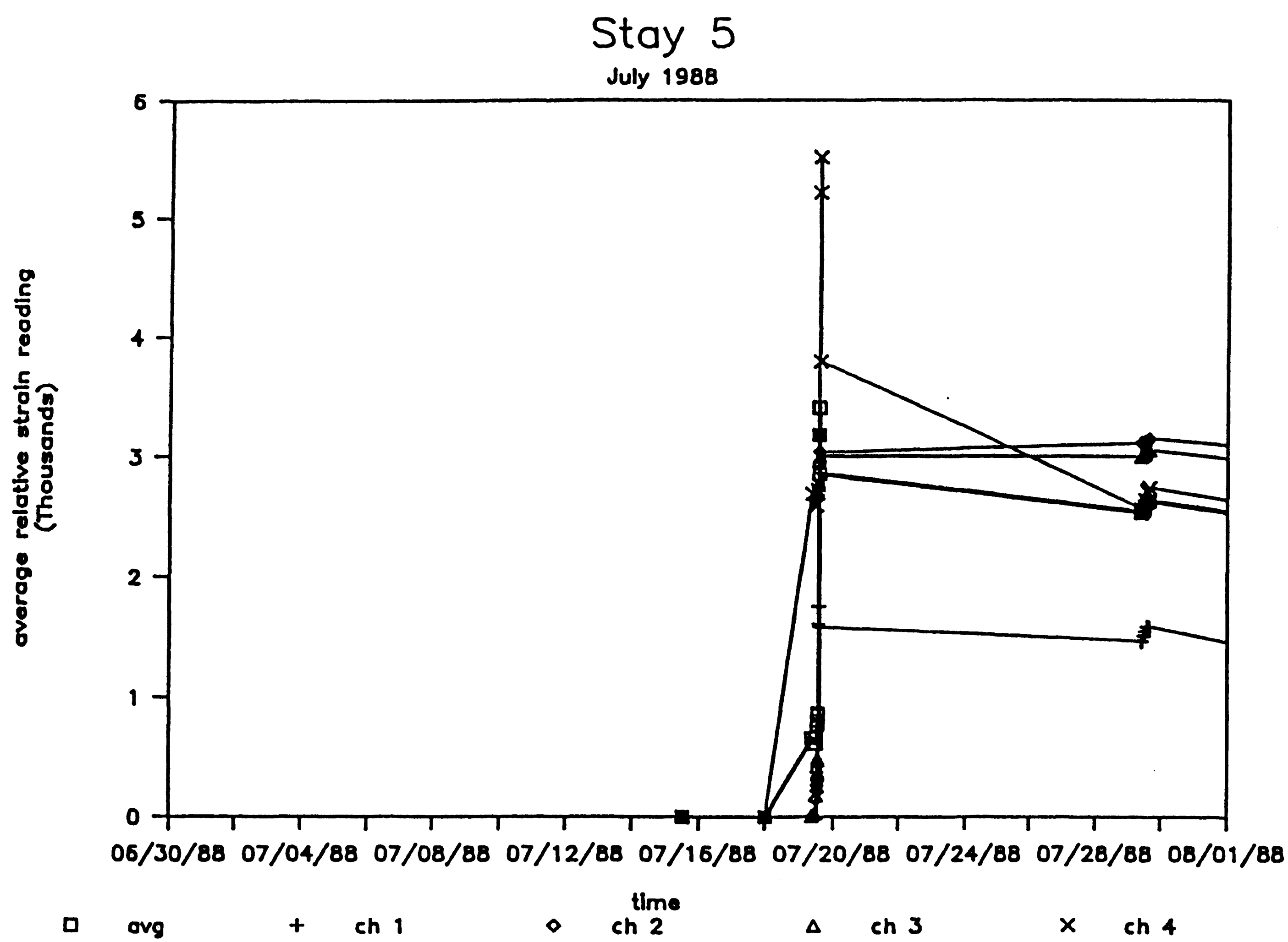

Figure 42. Stay S5, Individual Gages Strain Readings, July 1988

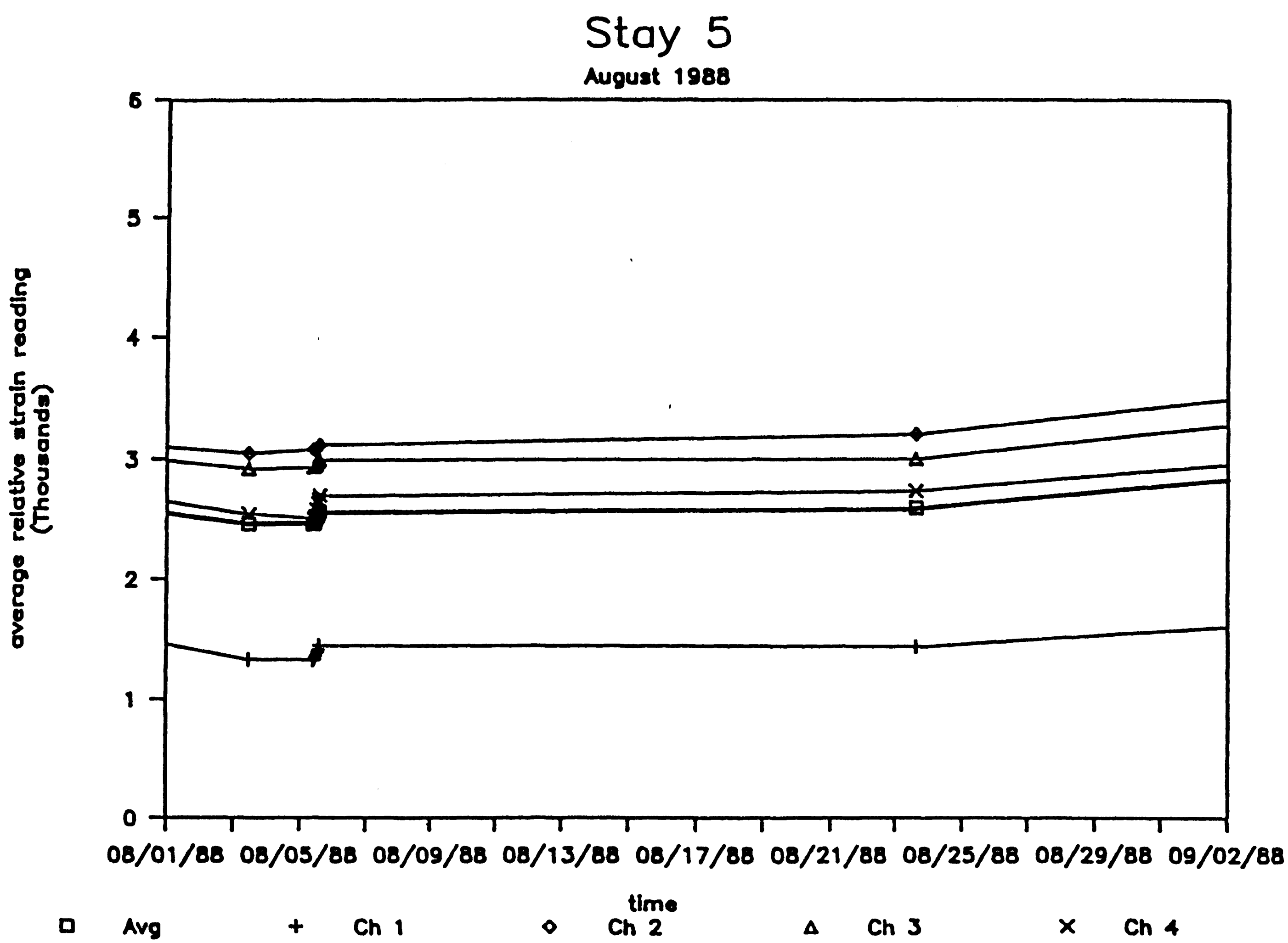

Figure 43. Stay S5, Individual Gages Strain Readings, August 1988

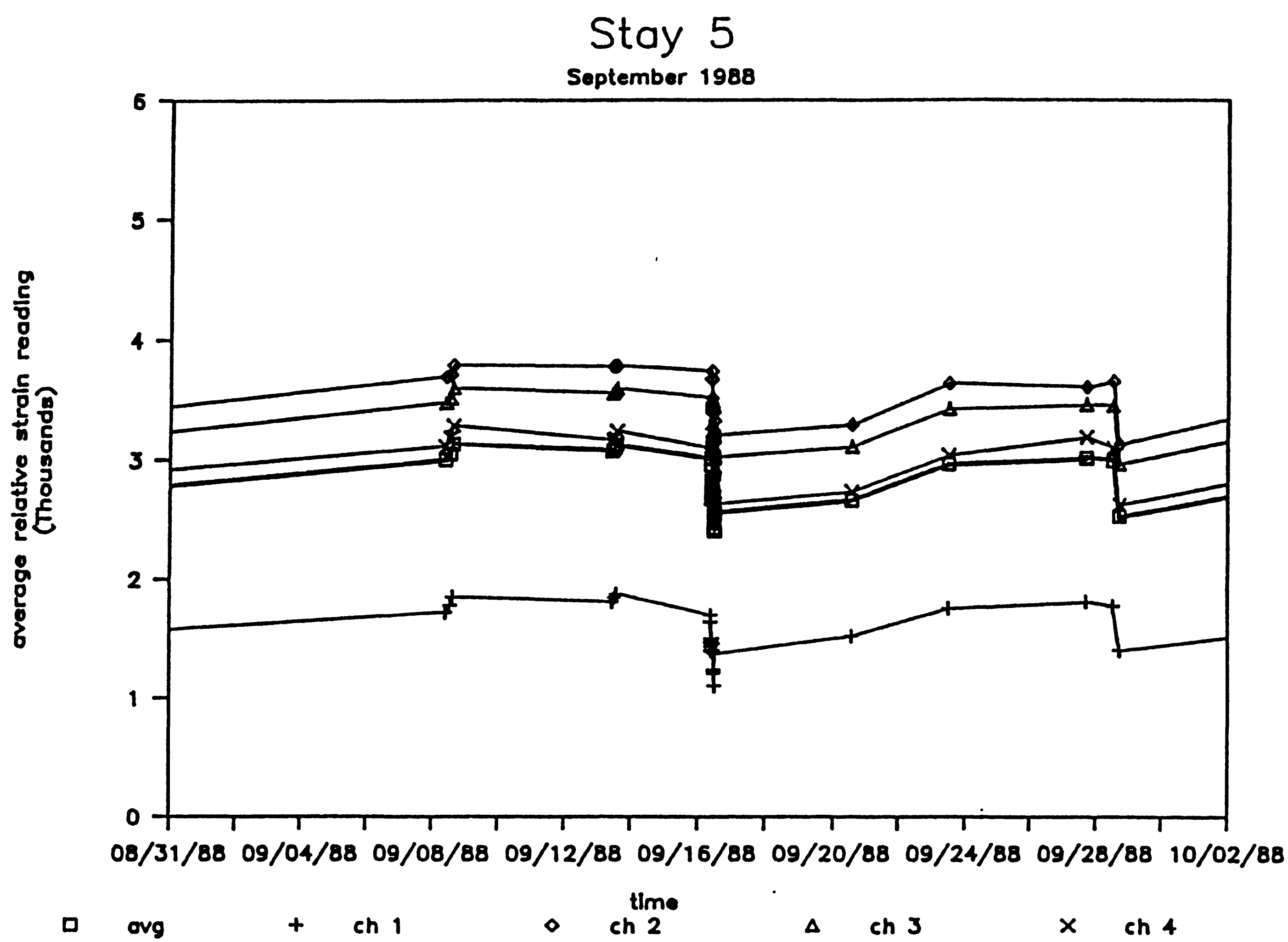

Figure 44. Stay S5, Individual Gages Strain Readings, September 1988

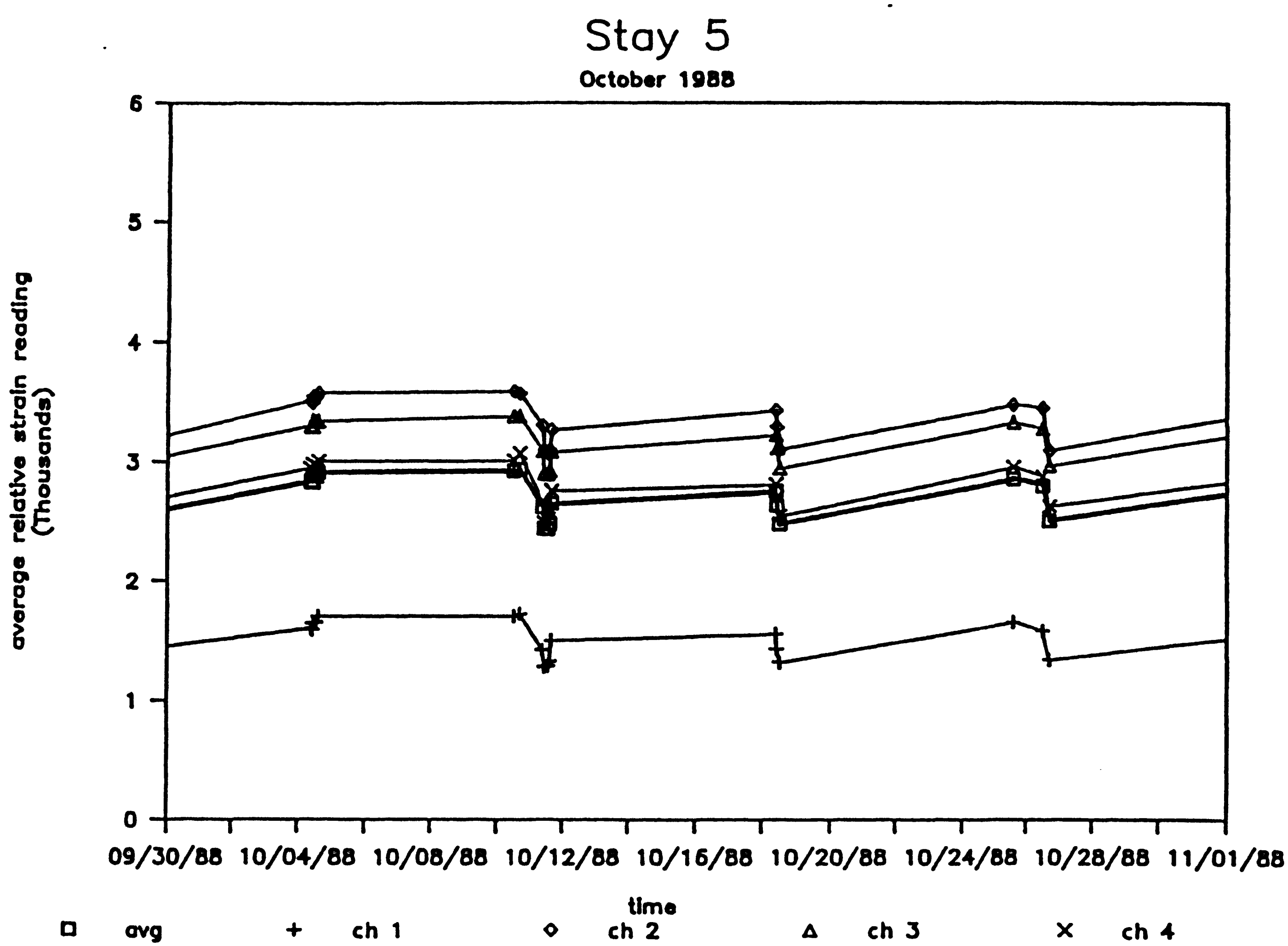

Figure 45. Stay S5, Individual Gages Strain Readings, October 1988

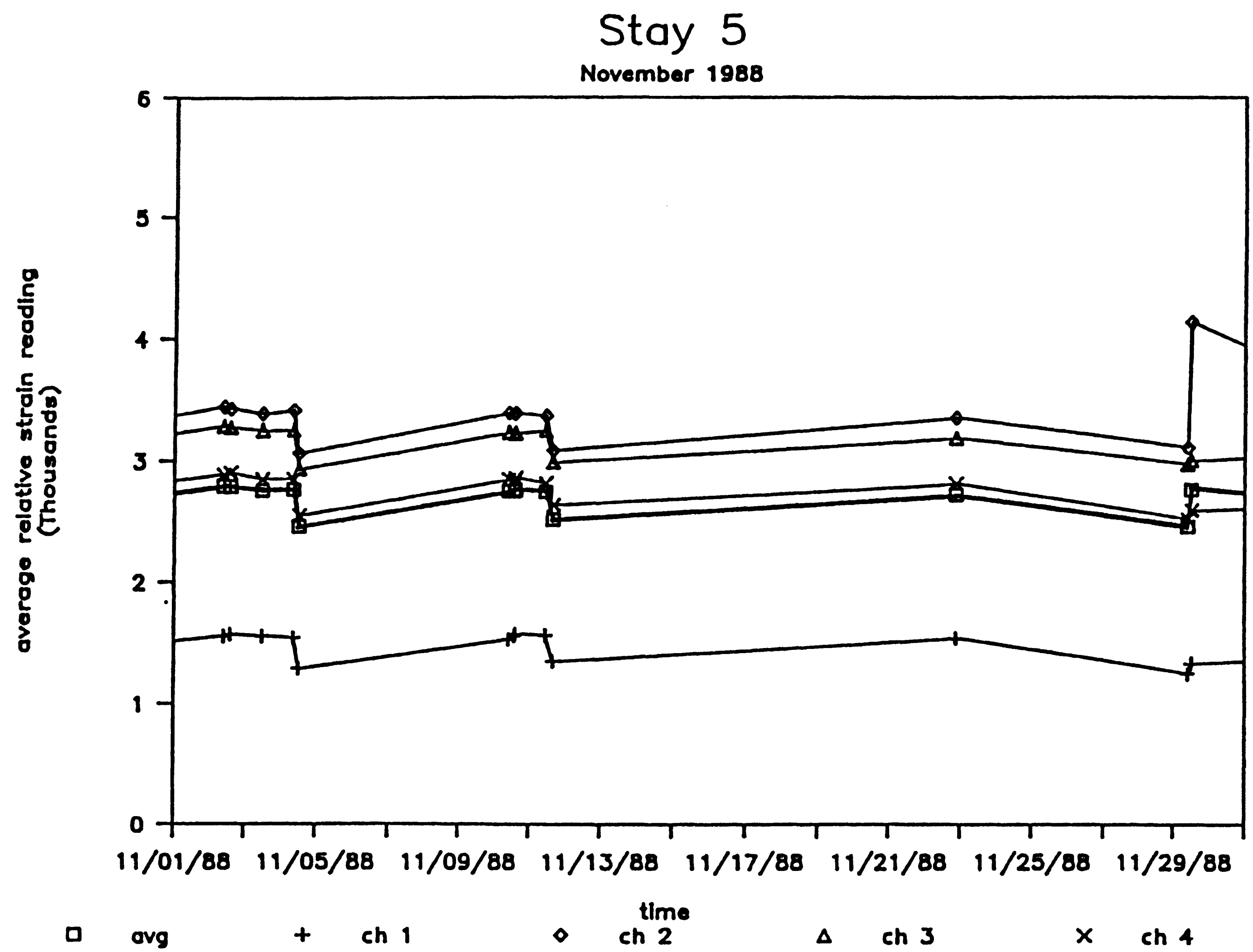

Figure 46. Stay S5, Individual Gages Strain Readings, November 1988

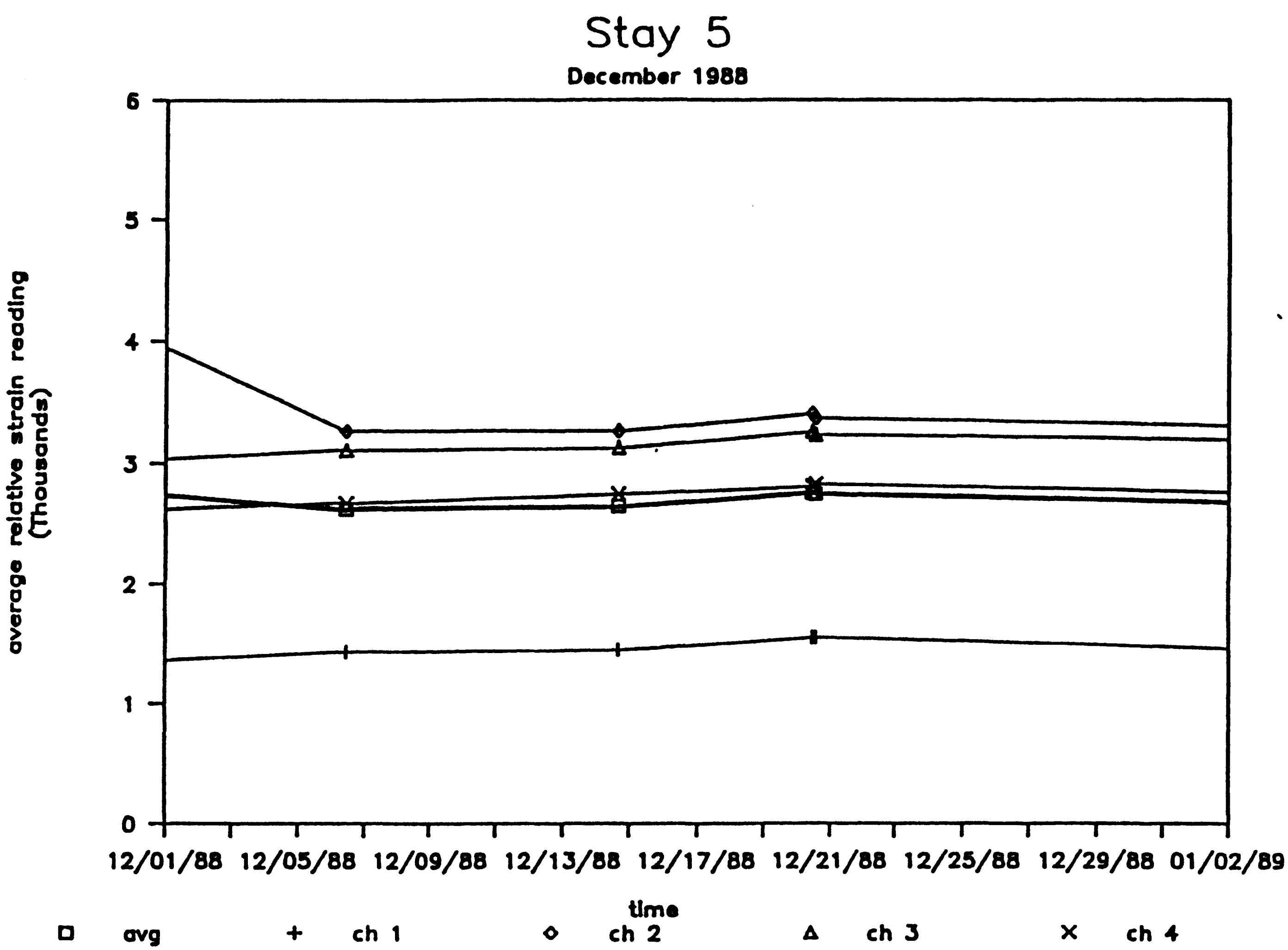

Figure 47. Stay S5, Individual Gages Strain Readings, December 1988

reported that, during tensioning, a considerable amount of noise was heard emanating from the strands. The investigators had already observed during gage installation that there was considerable sag in some of the strands and that a number of the strands were twisted around or pinched by other strands. Thus, it was concluded that the observed range of strains had, in fact, occurred. It is felt that the principal factors contributing to the large range of observed strains during tensioning include the presence of initial strains caused by strand slippage in some of the strands and the variation in slack in the various strands. It was concluded that the difference in strain readings from the individual strands would seem to indicate that the individual strands are not stressed to the same level.

This tentative conclusion was further supported by examination of the strain data obtained during tensioning of the other stays. These data are given in Table 1. It was contemplated to present the mean and variance of the data, but there did not appear to be a large enough set of data points for this approach to be meaningful. Consequently, the mean strain value, the difference between the largest and smallest value, and the percentage of the range relative to the mean are given. It is seen from the data in Table 1 that a 25 to 30 percent variation in the strains measured, relative to the mean, ocurred with all stays instrumented during tensioning and that stay 5, for which considerable shifting of the strands during tensioning was observed, had more than 83 percent variation. This suggests that the tensioning procedure may lead to a significant range of strains in the individual strands and that some strands could be overstressed and others understressed. The relative consistency of the data during subsequent events lends further credence to this suggestion.

Table 1

Strain Data Obtained During Stay Tensioning

	Stay Number			
	1	2	5	7
Date tensioned	3/16/88	4/2/88	7/19/88	9/28/88
Measured strains	2857	2120	1766	2562
	2511	2030	3061	2766
	2100	2014	2985	2821
	2471	2030	1190	2047
	2540	—	—	2338
Average strain	2485	2147	2250	2507
Strain range	757	526	1871	774
Strain range %	30%	25%	83%	31%
Average strain + Target strain =	99.4%	85.6%	90%	100.3%

CONCLUSIONS

This report documented the electrical resistance strain gage measurements on the cable stays taken as part of an ongoing research project on the field instrumentation of the I-295 cable-stayed bridge. Analysis of the data presented is still underway. However, based on the presented data, it is possible to draw some conclusions concerning the measured responses of the cable stays.

1. Stay-cable gage readings taken before and after stay tensioning reflected changes in strains in the instrumented cables relatively consistent with the expected strains. There appeared to be some tendeny to underestimate the strain during initial tensioning.

2. The strains measured in the stay-cable strands being tensioned displayed considerable variability, consistent with the different degrees of slackness and twist of the individual strands.

3. The strain increments measured in the stay-cable strands during events subsequent to initial tensioning were considerably more consistent than the values obtained during tensioning and reflected the expected behavior of the strands during these events.

4. The measured strains in the stay cables were influenced by temporary and permanent post tensioning as well as by the installation of subsequent stays and the lifting of segments.

REFERENCE

Baber, T. T.; Hilton, M. H.; McKeel, W. T., Jr.; and Barton, F. W. (1988). *Field monitoring on the I-295 bridge over the James River: Instrumentation installation and construction period studies.* Charlottesville: Virginia Transportation Research Council.