BROADWAY BRIDGE RALL WHEEL STUDY

Volume I

November 2012

Client: CH2M Hill, Inc.

Owner: Multnomah County, OR

Broadway Bridge Rall Wheel Study

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Purpose of Study

The Broadway Bridge is a double leaf Rall Type Bascule Bridge built in 1912, that spans across the Willamette River in Portland Oregon. The uncommon feature of this bridge is the design of the Rall Wheel pair as the dead load support system for each leaf through its range of motion. Each Rall Wheel is 100 inches in diameter, and rides along a cast steel track that is mounted to the bascule towers, approximately 30 ft above roadway level. During the past 10 years, personnel from Multnomah County have been monitoring certain symptoms of degradation and surface material failure of the Rall Wheel Assembly. Most notably, the North-West location, the lateral guide of the track has formed a crack and propagated approximately 13 ft of the 17 ft long side rail. In addition, the west bascule leaf has been surveyed and it was measured that the South wheel travels approximately 3 inches, more than the North.

As a result, the County selected Hardesty & Hanover to develop a plan and inspection focusing on the condition of the Rall Wheel Assembly (Wheel and Track). The plan also includes a complex system of instrumentations to monitor the loads seen at adjacent components (control struts & track towers) in order to assess the overall operation of the system. The plan was implemented and necessary data collected during the week of September 14, 2011.

The purpose of the Study is to estimate the remaining service life of the Rall Wheel Assemblies (Wheel, Shaft, bearing, track – defined earlier) in which the Bridge will no longer function reliably and predictably. The estimated service life will be the basis for a plan to replace the Rall Wheels understanding that they have reached the end of their useful service life. In addition, the recommended plan will include the replacement of the affected components (i.e. control strut bearings) and develop a conceptual discussion for replacement of the Rall Wheel and estimated construction schedule.

Executive Summary

The Rall wheel operation was observed and measurements were collected throughout the multiple bridge operations during the site visit by Hardesty & Hanover between 9/14/2011 and 9/18/2011. The Rall wheel assemblies were visually inspected to assess the wear and damage reported.

During the site visit to the bridge the week of September 14 through September 19, 2011, instrumentation and strain gages were installed at various locations on the track column, track girder and control struts. The existing strain gages on the operating machinery intermediate shafts were also utilized to measure the relative machinery loads during operations. Multiple operations of the bascule leaves were performed and measurements taken via electrical data logging equipment. These measurements indicate that components are experiencing in some cases uneven loads, unintended load shifts, high and low peaks. These observations are consistent with worn and misalignment of components.

All locations show wear, with the North-West location noted to be the most severe. Analysis of the surface failure confirms components are at the end of their service life. It is concluded that the Rall wheel assemblies should be replaced within the next 3 to 5 years.

Description of Bridge

The Broadway Bridge consists of a movable double leaf Rall bascule at the middle of the bridge and two fixed approach spans on each side. The distance between the two bascule bridge seats is 278 feet. Each of the approach fixed spans are approximately 208 feet long.

The bridge is one of the rarest and most complicated type of movable bridge in operation today.

When the bridge is in the seated position the lower end of the movable leaf truss sits in a bearing seat on the pier. The rotation of each leaf is resisted under live load by anchor struts. The anchor strut provides a tension force to the top of the bascule span trusses. There are two locks at the span end of the bascule leaves which transfer vehicle live loads from one leaf to the other leaf.

Each movable leaf is supported by two cast steel Rall wheels which roll on a horizontal cast steel track, mounted to the fixed tower structure of the flanking spans. The Rall wheels are located outboard of each of the bascule span trusses. Each Rall wheel is 100 inches in diameter, and carries the entire dead load of the bascule leaf through the range of movement during operation. The rotation of the span is ensured by the Control Strut pinned to the counterweight and to the flanking span structure (i.e. controls the span rotation, rather than translating along the Track). Two electric span drive motors drive a common spur gear through a differential gear set to two gear trains located in a fixed house on the flanking span truss (above roadway level). The machinery (main pinions) engage with flat gear rack segments mounted on the Operating Struts, which transfer the machinery load to the bascule via pinned connections. The Operating Strut gear rack is allowed to pivot on top the main pinion gears with respect to the bascule truss incline during operation.

During operation the operating struts pull on the bascule span causing the bridge to move back linearly at the center of the Rall wheel shaft while rolling on the wheel. The control strut connects a point on the counterweight to a point on the fixed span. As the bridge rolls back the control strut causes the rotation of the span by only allowing the point on the counterweight to rotate at a set radius about the pin connection on the fixed span.

History of Repairs

The following is a general list of major project milestones:

- Bridge Built and Opened – 1913
- Weld Repairs to NW Roller – 1980’s
- Replacement of Control Struts and Stiffening of the NW Roller - 1982
- West Machinery Rehabilitation – Early 1990’s
- Replacement of Anchor Struts – 2001
- East Machinery Rehabilitation – 2003
- Deck Replacement – 2005
- Added Trolley Tracks and Span Lock Replacement – 2011

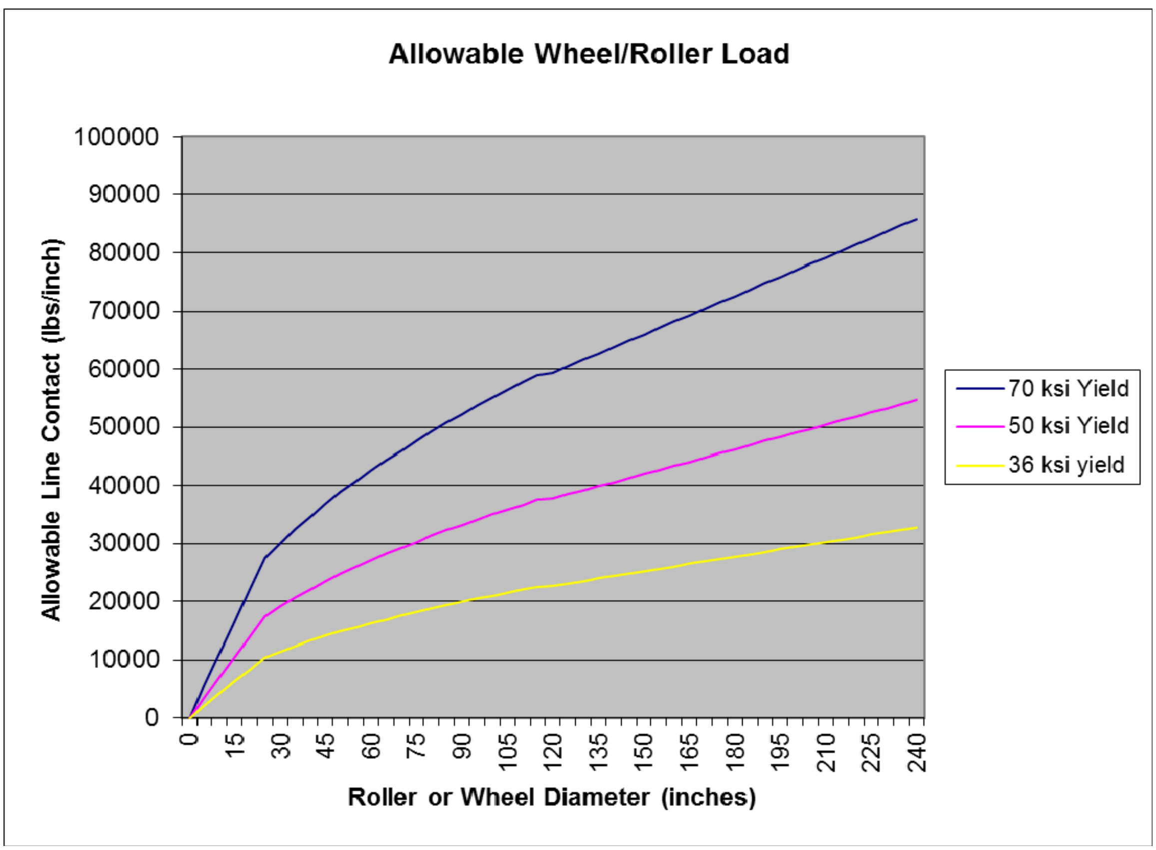
Analysis of Rall Wheel and Track

One of the key elements of the design of a Rall Bridge is the track and Rall wheel. These components would be most similar to the curved treads and tracks of a Rolling Bascule Bridge. However it is noted that rolling bascule bridges tend to have a rolling diameter of greater than 120" and the Rall wheel for Broadway has a diameter of 100". In the early 1900's, at the time the bridge was built, the design codes were still relativity new and in development for the allowable line contact for rolling bascule bridges. In the 1920's a considerable amount of research was performed regarding the allowable line contact of large rollers on flat plates by Wilbur M. Wilson, at the University of Illinois. Later, his research would be used to form the basis of the allowable line contact for rolling bascule bridges used in both the AREMA (formally AREA) and AASHTO movable bridge design codes.

The current AASHTO code has the following formulas for rollers and rolling segments in motion:

(I)	D < 25":	((Yield-13,000)/20,000) * 400 * D
(II)	D = 25" up to 125"	((Yield-13,000)/20,000) * 2000 * D^0.5
(III)	Rolling Segments D > 120"	((Yield-13,000)/20,000) * (12000 + 80*D)

It is noted that formulas (II) & (III) have an overlap of between 120" and 125" diameters. The results using either formula vary by less than 2% in this range, with using formula (III) being slightly more conservative. A graph of the allowable line load is shown below for material having a 36ksi, 50ksi and 70ksi yield strength.



From the original drawings and information found in the book "*Movable Bridges, Volume I-Superstructure*", written by Otis Hovey, published 1926, the load per Rall wheel is listed as 2,000,000 lbs. It is also listed that the castings for both the roller and track is a nickel chrome steel with the approximate following properties:

- Elastic Limit: 52,000 psi
- Ultimate Tensile Strength: 102,000 psi
- Elongation not less than 15%
- Reduction of area at fracture not less than 17%

In 2004 a sample of the casting (see appendix for copy of test reports) was removed and tested with the following results:

- Yield Strength: 52,800 psi
- Ultimate Tensile Strength: 108,000 psi
- Elongation not less than 12%
- Reduction of area at fracture not less than 14%

These results are similar to what had originally been specified. It is noted that the percentages of elongation and reduction of area however were found to be less than what had been specified, indicating the material is slightly more brittle and less ductile.

In 2005 several hardness readings had been measured on the wheel and track on both used and unused surfaces (see appendix for a copy of "Broadway Bridge Rall Wheel Rolling Contact Fatigue Investigation"). The results generally indicate that the used surfaces are now harder than the unused surfaces. This is a result of the material being work hardened at the surfaces over the years. It is also reported that the surfaces have pitting and spalling indicative of rolling contact fatigue failure. Additionally, the report also lists an estimate of a material strength of 107,000 psi and a yield strength range of 71,700 psi to 91,000 psi based on the hardness results. The estimated yield strength in the report has a high range between the maximum and minimum. Therefore the yield strength estimates are not used in analysis to follow.

A maximum wheel load of approximately 2,080,000 lbs. was noted on the original Rall wheel drawing. This load is used for the analysis.

The wheel has a diameter of 100" and a width of is 40". Using the load on the wheel as 2,080,000 lbs., the linear line contact would be 52,000 lbs./inch. Note that the linear contact calculated is based on 40" and the linear contact would increase if the effective width is reduced.

<u>Allowable Linear Contact Load (AASHTO formula)</u>

Using the AASHTO formula, the allowable line contact would be 39,800 lbs./inch for a material with a yield strength of 52,800 psi as tested in 2004. The allowable line contact calculated is 76% of the actual required line contact of 52,000 lbs./inch.

Calculated Contact Stress

The contact stress of the Rall wheel on the track was also calculated using the Hertz contact stress equations listed in "*Roark's Formulas for Stress and Strain, 8th edition*", authored by Young, Budynas and Sadegh. A modulus of Elasticity (E) for both the roller and tracks of 30,000 ksi and the poissons ratio of 0.3 was used for the calculation.

Using these parameters the contact stress is calculated to be 73.8 ksi with the equation listed below:

Equation for cylinder on a flat plate:

Contact Stress (max) = 0.591 * (p * E / K) ^ 0.5 where: p = 52,000 lbs/inch and

K = D = 100"

Allowable Contact Stress/Fatigue Strength

Using the AASHTO allowable line loading for a 100 inch dia roller with a yield strength of 52.0 ksi, the allowable contact stress is calculated to be 63.9 ksi.

Another way to calculate the surface contact fatigue strength of steel is from the material hardness value. An equation for this from "*Mechanical Engineering Design, 5th edition*", authored by Shigley and Mischke is given below:

Equation for Surface Fatigue Strength:

Allowable Contact Stress = $S_C = (0.4 * H_B) - 10ksi$ where: H_B = Brinell hardness

From the hardness test taken on the unused portion of the wheels and tracks a minimum of 213 Brinell was reported. Using this value the contact strength would be 75.2ksi.

The following tables summarize the allowable contact stress/fatigue strength based on various yield stregths and the effect of contact stress based on a reduction of the effective width:

ALLOWABLE CONTACT STRESS/FATIGUE STRENGTH				
YIELD STRENGTH (KSI)	APPROXIMATE HARDNESS (BRINELL) (See note *)	AASHTO ALLOWABLE LINE BEARING (KIP/INCH)	AASHTO ALLOWABLE CONTACT STRESS (BASED ON ALLOWABLE LINE BEARING) (KSI)	FATIGUE CONTACT STRENGTH (BASED ON HARDNESS) (KSI)
40	175	27.0	53.2	60.0
50	190	37.0	62.3	66.0
60	210	47.0	70.2	74.0
70	225	57.0	77.3	80.0
80	250	67.0	83.8	90.0

Note *: Hardness estimated from ASTM A668 material specifications.

BROADWAY BRIDGE RALL WHEEL AND TRACK LINE BEARING/CONTACT STRESS DUE TO REDUCED EFFECTIVE WIDTH			
PERCENT CONTACT WIDTH OF ORIGINAL	EFFECTIVE WIDTH (INCHES)	LINE BEARING REQUIRED (KIPS/IN)	CONTACT STRESS (KSI) (Hertz formula)
100%	40	52.0	73.8
90%	36	57.8	77.8
80%	32	65.0	82.5
70%	28	74.3	88.2
60%	24	86.7	95.3
50%	20	104.0	104.4

Visual Observations

The Rall wheels and tracks were observed through multiple operations. The contact surfaces of the wheel and track were generally pitted and many impressions were present of the previous debris that was left on the track during past operations. Also, several defects were noted on the wheels and tracks.

The North-West wheel and track was found to be in the worst condition. This wheel had been previously weld repaired. The past repairs were performed on the wheel contact rim section as well and the wheel flange. This wheel has also been retrofitted with through bolts to keep the wheel together in the event that circumferential cracks propagated around the wheel. The track has also had a rail added to help guide the wheel during operation. This rail was welded on the outboard edge of the track. The rail joint between the added rail and the track has failed.

The surfaces of all the Rall wheels and tracks were checked with a straight edge. These surfaces were found not to be flat.

Detailed Observations for each location are listed below:

North-West (See Photo M-001 for general view at this location)

The wheel and track contact surfaces and overall condition at this location was found to be the worst out of the four locations.

The contact surfaces of the wheels had some rusting, pitting and spalling (See photos M-002 & M-003). Several cored holes were observed. One cored hole was made through a crack in the surface (See photo M-004 & M-005). There was also a group of four cored holes at the upper left corner of the wheel (See photo M-006). On the wheel the visible signs of material differences were observed. These were generally surfaces areas that are inbetween areas where the wheel webs are. It was also observed that there are some areas where the material appeared to have lapped over. Most likely these are the areas where wheel repairs have been performed in the past (See photos M-007 through M-010). Two other cored holes were observed on the lower portion of the wheel surface (See M-011). A straight edge was placed across the width of a sample location of the wheel. The surface was found to be worn and wavy (See photos M-012 & M-013). The wheel rim was previously damaged and weld repaired (See photo M-022). During a bridge operation the wheel contact surface and rim/rim repair was observed (See photos M-015 & M-016).

Generally the track contact surface condition matched the wheel surface. A straight edge was laid across the track. This surface was also found to be worn and wavy (See photo M-017). The surface of the track had many areas of rusting, pitting and spalling (See photo M-018). The North-West Track had a piece of rail added to the outboard side of the track. The purpose of the rail was most likely to help guide the wheel due to the previously damaged inboard wheel flange. Currently the rail has failed and separated from the track. It is most probable that the failure is the result of the wheel pressure/rubbing against the rail during operation. The majority (approximately 13ft of the total 17ft length of rail) of the weld that connected the rail to the track is cracked (See photos M-019 through M-022). It is noted that the wheel does not contact the rail during the initial travel from the closed position. The portion of track where the wheel sits when the bridge is in the closed position was observed during a bridge operation. No usual observations were noted (See photo M-023).

South-West (See Photo M-024 for general view at this location)

The wheel and track contact surfaces and overall condition at this location was found to be similar, but slightly less severe than the condition at the North-West.

The contact surfaces of the wheels had some rusting, pitting and spalling (See photo M-025). A void/porosity defect was observed on the upper portion of the wheel (See photo M-026). One cored hole was observed on the lower wheel surface (See photo M-027 & M-028). A straight edge was placed across the width of a sample location of the wheel. The surface was found to be worn and wavy (See photo M-029). During a bridge operation the wheel contact surface and rim was observed. No unusual observations were noted (See photos M-030 & M-031).

Generally the track contact surface condition matched the wheel surface. The surface of the track had many areas of rusting, pitting and spalling (See photos M-032 through M-034). A straight edge was put across the track. This surface was also found to be worn and wavy (See photo M-035). The portion of track where the wheel sits when the bridge is in the closed position was observed during a bridge operation. No usual observations were noted (See photo M-036).

North-East (See Photo M-037 for general view at this location)

The wheel and track contact surfaces and overall condition at this location was found to be similar, but slightly less severe than the condition at the other three locations. At this location it appears that more items/debris were present on the contact surfaces during operation at some time in the past.

The contact surfaces of the wheels had some rusting, pitting and spalling. At this location there appeared to be more impressions of items left on the track during operation (See photo M-038). One cored hole was observed on the wheel surface level with the shaft (See photo M-039). A straight edge was placed across the width of a sample location of the wheel. The surface was found worn and wavy (See photo M-040). During a bridge operation the wheel contact surface and flange was observed. A cored hole was observed on the upper wheel surface as the bridged opens (See photos M-041 & M-042). It appears that washers were left at some time on the wheel/track contact surfaces making permanent impressions (See photo M-043). As the bridge reached the nearly open position another cored hole was observed (See photos M-044 & M-045).

Generally the track contact surface condition matched the wheel surface. The surface of the track had many areas of rusting, pitting and spalling and impressions of foreign material left on the contact surface at some time in the past (See photo M-046). The portion of track where the wheel sits when the bridge is in the closed position was observed during a bridge operation. No usual observations were noted (See photo M-047).

South-East (See Photo M-048 for general view at this location)

The wheel and track contact surfaces and overall condition at this location was found to be similar to the condition at the South-West.

The contact surfaces of the wheels had some rusting, pitting and spalling (See photos M-049 & M-050). One cored hole was observed on the upper wheel surface along with a moderate impression (See photo M-051). A long impression was observed on the wheel surface level with the shaft (See photo M-052). During a bridge operation the wheel contact surface and flange was observed (See photo M-053). A cored hole was observed on the wheel surface as the bridged opens (See photos M-054 & M-055). As the bridge reached the nearly open position a moderate impression adjacent to the wheel flange was observed (See photo M-056).

A straight edge was put across the track. This surface was also found worn and wavy (See photos M-057 & M-058). Approximately a foot away from where the bridge sits in the closed position a crack was observed on the track out board edge. The crack was approximately 2” long (See photos M-059 & M-060). Generally, the track contact surface condition matched the wheel surface (See photos M-061 & M-062). The portion of track where the wheel sits when the bridge is in the closed position was observed during a bridge operation. No usual observations were noted (See photo M-063).

Measurements & Survey Data

Various locations of the structure were evaluated using strain gages during the full range of bridge operations. Locations that the strain gages were installed included: The main column supporting the track girder, the outer webs of the track girder, the control strut and the main pinions. The angle of opening, Rall wheel travel, shaft rotations of the operating machinery and the angle of tilt of the track was also recorded to correspond to the data collection of the strain measurements. The last day of the investigation included adding shims to the bridge seat and recording the main column strain, main pinion strain and vertical movement of the main column.

Wheel offset measurements were taken along with the length of Rall wheel travel at each location (See table M-1 for measurements).

The following is a summary of the measurements and data that was recorded during the site visit (See Appendix F for graphs of the data):

<u>Strain gage</u>

Main Load Columns (supporting channel ends of track girders)

Uniaxial gages for longitudinal strain (vertical) were installed on the main support columns. (See photo M-064) The purpose of this measurement is to determine if load on wheels is relieved or changes when leaf is operated and as bridge is seated onto the bearing shoes.

The gages were initially installed with the bridge in closed position. Therefore the measurement will indicated any change from the loaded condition with the bridge in the closed position.

The measurements showed a rapid change in load at the initial start of operation and then an approximate linear change in load to the open position. This is an indication that currently a portion of the load is relived as the bridge is seated. The last day of the inspection included adding shims to the bridge seats and recording the strains in the columns. A noticeable change in the strain was observed, verifying that a portion of the dead load is transferred from the Rall wheel to the bearing shoes located on the pier.

Control Struts

Uniaxial gages were installed on control struts. (See photo M-065) One gage was installed on the top flange (2 ½” down from the edge) of the strut and a second gage was installed on the bottom flange (2 ½” up from the edge) of the strut. The average of the strain of these two gages would be the axial strain in the strut. The amplitude of the strain to the average would indicate that there is a bending moment in the strut. The purpose of this measurement is to monitor force changes and the differences in the top and bottom gages during operation.

The measurements for the North-East, South-East & South-West had top and bottom strain that were fairly similar. For the North-West the top and bottom strain varied by a moderate amount indicating a longitudinal bending moment (bearing friction) or a transverse bending moment (parallel pin misalignment or bridge misalignment during operation) at this location.

Rall Track Girders

Strain gages (45º rosettes / 2-arm) were mounted on the outside of each track girder web. (See photo M-066). A (2-arm) gage was installed both sides of the track girder at approximately 7' from the position were the Rall wheel is located with the bridge seated and 17" down from the top of the track girder. The purpose of this measurement is to monitor transverse load distribution as wheels roll on track.

The measurements for the North-East, South-East & North-West were generally similar indicating fairly even wheel load across the track. The South-West measurements indicated a moderate difference in strain from the inboard and outboard gages indicated uneven wheel loading across the width of the track.

Operating Struts

Strain gages (pairs of 2-arm) rosettes were previously installed on each of the 2nd reduction intermediate shafts (See photo M-067). These measurements are used to determine the torque at the main pinion shaft which can be used to calculate the force in the operating strut. The purpose of this measurement was to monitor the operating strut axial force and the difference in the force from North to South provided by the rack and pinion.

Linear transducers/measurements

Main Load Column (supporting the North-East track girder)

A weight attached to the bottom side of the track girder was hung down to the top of the pier adjacent to the bridge seat. A dial indicator and a linear displacement sensor used to detect movement of the weight when shims were added to the East bridge seats (See photo M-068). The purpose of this measurement was to observe the vertical rise of box girder (track girder support) due to closing action of span while shims were added to the East bridge seat. This measurements/observations should correlate to the measured strain change in the main columns.

It was observed when maximum amount of shims used during the testing were added that the column had lengthened 0.019". The deflection corresponded to the bridge transferring the load to the bridge seat and relieving the Rall wheel.

Rall Wheel Travel

A spool assembly with an encoder that the County had previously used for measuring Rall wheel travel was utilized. (See photo M-069) The purpose of this measurement was to record the horizontal movement (travel) of wheels and note any differences in the North and South travel of each leaf.

The initial method proved difficult to conclude a noticeable difference in travel from North to South. A secondary method was implemented and the overall length of travel was measured using a steel tape (See table M-1). From these measurements the East span North and South Wheels had similar length of travel and on the West span the South wheel traveled 4 ½ " more than the North wheel.

Operating Strut Travel

An encoder mounted to an intermediate shaft of each of the secondary gear frames was used to record the number of revolutions of the shaft. (See photo M-070) The purpose of this measurement was to record the difference in travel of the North and South operating struts.

The counts at the start and stop of the opening and closing cycles were taken and recorded on each leaf for multiple tests (See table M-2). From the counts recorded at the stop and start of multiple bridge operations, the East and West bascule spans had North and South machinery shaft counts were similar during operation. However it was noted that the County had previously measured a difference of 1 ½ " between the North and South on the West leaf. This difference is consistent with the difference in the Rall wheel travel on this leaf. It is concluded that the measurement of absolute counts may not be accurate enough through the backlash and back-and-forth movement of the gears during operation to pick up the small relative difference in travel of the two operating struts.

Level

Rall Wheel Track (transverse and longitudinal)

Two inclinometer were mounted (90 degrees apart in plan) at end of the Rall Wheel Track to measure the transverse and longitudinal change in angle of each of the tracks. (See photo M-071)

The change in transverse change in angle during operation of all tracks was minimal. The change in longitudinal change in angle during operation of all tracks was minimal, except for the South-West. At this location the change in longitudinal angle was approximately ½ degree during operation. This is an indication that there is a difference in the alignment of the tracks during operation.

Straight Edge

Rall Wheel and Track Offset and Travel

Measurements were taken and recorded for the transverse offsets of the wheels to edge of track at various bridge positions. The overall length of travel of the Rall wheels was also taken and recorded (See Table M-1). The measurements indicate that there was some transverse movement in the wheel during operation. The maximum was found on the South-East to be approximately $^{3}/_{4}$". The transverse movement at the other three locations was approximately $^{3}/_{8}$".

Additional Survey Information or Reported Conditions

- In 2010, it was reported by the County that the South-West Rall wheel travels over 3" more that the North-West Rall wheel. Also it was found that the North-East Rall wheel travels 1" more than the South-East Rall wheel.

- In 2010, it was reported by the County that the South-West Rall wheel track is approximately 3/8" higher than the North-West track.

- County Personnel documented interference in the form of rubbing on the thrust face of the bearing at the operating strut fixed end connection on the West leaf. This is an indication that the operating struts are "twisting" or "racking" with respect to the leaf pulling unevenly at the Rall wheels during operation.

- County Personnel documented housing bolt failure at the anchor strut bearings (fixed end) on the East leaf.

Conclusions

Analysis of Rall Wheel & Track

The analysis of the wheel and track was performed using two methods. The first method was performed using the AASHTO allowable line contact formula (6.6.2.6 Bearing on Rollers) which is based on the materials yield strength. A yield strength of 52,800 ksi was used per the test results reported in 2004. Using this yield strength the allowable line contact was calculated to be 39,800 lbs./inch. For this bridge load and wheel dimensions, results in the line contact being 33% over the AASHTO allowable. It should be noted that there is a safety factor included in the AASHTO formula so that the allowable line contact is less than the maximum limit.

The second method used is based on the contact fatigue strength of the material. This method estimates a contact strength of steel based on the hardness. Using the minimum hardness results from 2004 (213 Brinell), the contact surface fatigue strength of the 75.2 ksi was calculated. The contact stress was calculated to be 72.4 ksi which is slightly below the surface fatigue strength

These components have started to show the initial signs of surface failure as noted in the visual observation section. Also the effective width is progressively being reduced as the surface deteriorates and from impressions left of debris on the tracks during operation, which will increase the actual contact stresses and linear loading.

Visual Rall Wheel & Track Observations

All track surfaces were found to have a minimum of moderate pitting, spalling and corrosion. Also the surfaces of the wheels and tracks were found to be worn and irregular surface. These conditions will impact/reduce the effective width of the roller and track. This in turn will increase the contact stress. Additionally, it was found that the West leaf is not tracking linearly. It is noted that wear, corrosion, pitting and spalling can be found in similar cases of the curved treads and tracks of rolling lift bascule bridges. This type of failure of the contact rolling surfaces is typically a slow process over time.

The wear patterns, pitting and spalling indicate that the components have already reached the fatigue limit for contact stress. In addition, as the effective width is reduced the contact stress will increase further accelerating the deterioration of the surfaces.

As reported, it was confirmed that the West leaf is not tracking linearly. The results from observations performed by the County and during the inspection that the West leaf Rall wheels travel a difference of between 3” to 4 ½” and the East leaf Rall wheels travel a difference of between ¼” and 1” during operation. The travel of the Rall wheels should be monitored periodically to detect if there are any significant changes in the tracking of the two leafs.

Control Strut and Track Girder

The electronic measurements also show evidence of uneven loading. The control strut measurements show that load is distributed unevenly between pairs and a portion of the loading will cycle back and forth from one side to the other, during operation.

During the investigation it also was found that the strain gage measurements at the North-West control strut had indicated the inboard and outboard measurements had a higher difference at this location. Due to the placement of the inboard and outboard gages when the values are similar they indicate an axial load and when they differ they would indicate a bending moment along with the axial load. The values recorded at the North-West is an indication of higher bending loads than the other locations. This could possibly be the result from higher bearing friction and misalignment due to wear. It is therefore recommended to replace the control strut bearings as part of the work. As part of this work an accurate survey could be performed on the bridge during operation to precisely locate/fabricate new components. A more accurate alignment of the components will promote a smoother more reliable bridge operation.

Generally, the track girder strain measurements are similar. It was noted that the South-West inboard and outboard strain measurements had a moderate difference, which could be an indication of uneven loading across the width of the wheel at this location.

Digital Levels and Track Column

The longitudinal angle measurements indicated a change in angle as the wheel travels which is expected. The South-West track the angle change was much higher (approximate magnitude of ½ degree versus less than 1/8 degree for the other locations). This is an indication of the tracks not being aligned with respect to one another and differential loading from one side to the other. The transverse angle measurements indicated that the tracks tilt in towards the inboard side as the Rall wheels roll back.

The main load column strain gage readings measured the load changes during operation. The main load column strain gages were also very beneficial when adding shims to the bridge seats to see how the bridge dead load is relieved from the Rall wheels. When adding the two 10 gauge shims it was found that the post strain gage changed by approximately 72 micro-strain. With a column cross sectional area of 153 square inches, the difference in strain measured equates to relieving 333 kips of dead load from the column/track.

With a bridge dead load of 2,000kips and taking into account the results of adding the shims to the live load supports during the site visit, it is estimated that a total minimum shim thickness of approximately1.5” would be needed to relieve the load.

Remaining Service Life

It is anticipated that the surface failure will continue until large pieces of “spalled” material will break off the wheel and potentially create and interference obstruction including landing on the track. Although this type of failure is a very slow process over many years (10 years plus) and is generally not catastrophic, it is assumed that the operation of the bascule leaves will become more problematic. It is assumed that the operating struts, control struts and adjacent components will continue to experience operational problems and wear will accelerate as the Rall Wheel and Track continue to degrade.

The electronic measurements (strain gages and digital levels) have shown that components are experiencing in some cases uneven loads, unintended load shifts, high and low peaks. These observations are consistent with worn and misalignment of components.

Based on the severity of wear and more importantly the additional operating problems it is apparent that the Rall wheel assemblies are reaching the end of their service life. It is therefore recommended to replace the Rall wheel, bearings, axles and Tracks at all four locations within the next 3 to 5 years in order to proactively avoid serious negative impacts in operation of the movable span. At the same time the control struts bearings should be replaced and aligned consistent with the new wheel and track components. The live load bearings, anchor struts and the operating struts may also require adjustment during the course of this work.

To increase the capacity of the contact surfaces, we recommend the replacement material to be an alloy steel with a minimum yield strength of 80,000 psi. The new components should be of welded steel to conform to modern processes, and detailed such that the contact areas are suitable forged steel material.

Until the Rall wheel assemblies can be replaced, it is recommended that the following items be implemented and to continue to be monitored and significant changes be recorded:

- Rall wheel operation and contact surfaces
- North-West track cracked rail
- Install survey monuments and monitor position (To rule out pier settlement as a cause)
- Operating Strut and Control Strut performance (Record any differences noted between the North & South on the West and the East leaves. Note any additional fastener failure)
- Anchor Strut performance (Record any live load bearing shoe differences noted between all four locations. Note any additional fastener failure)

Construction Discussion & Schedule

Construction Discussion

The major challenge in replacing the Rall Wheel is the transfer of the bascule leaf dead load to the pier. The bridge seat would be the likely jacking or support point for the Rall wheel replacement. It was confirmed that the heel bearing located at the pier relieved a portion of the load during the inspection. A more detailed analysis would need to be performed to see if the total dead load could be relieved by just adding shims to the bridge seat. If the total dead load can not be relieved by just adding shims to the bridge seats, it would necessary to develop a temporary jacking and support system to handle the remaining portion of the load.

It is noted that the clearance between the movable span and the fixed structure would need to be studied, taking in account the addition of shims or when jacking the bascule leaves. Also, the loading of the anchor struts, lower live load bearing and operating struts would need to be analyzed when the load is relieved by adding shims to the lower live load support or jacking the bascule leaves. It would also be recommended to consider adding temporary bracing in order to help aid the stabilization of the movable leaves during the performance of this work.

It is anticipated that the bascule leaves will need to be jacked from the pier simultaneously, to permit enough clearance for the removal of the track and the Rall Wheels. The bridge would be closed to navigation for this work, but can maintain vehicular traffic by building a temp asphalt ramp at the roadway heel joint. The light rail would require a temporary detour for the work, or possibility temporary track alignment.

The Rall Wheel (70,000#), would be removed by disconnecting the trunnion axle from the outboard side. Temporary scaffolding above the sidewalk would need to be constructed for this work.

With the axle removed, the wheel may be rolled to the rear portion of the track. At this location the wheel must be hoisted with a crane and lowered to truck or barge.

Removal of track (60,000#) can be accomplished by sliding back, and picking from roadway deck.

The new components are to be installed by reversing the operation sequence described.

The schedule, per corner, is outlined below and can be performed so that one lane of traffic, and one sidewalk is maintained throughout the duration. We anticipate the roadway access for component removal and delivery to be performed at night or non-peak hours.

Preliminary Construction Outline

Day 1 - Jack leaves to relieve load

Day 2 – Build temporary ramps

Day 3 – Removal - Axle

Day 4 – Removal – Wheel from track

Day 5 – Removal - Wheel from bridge

Day 6 – Removal - Track from tower

Day 7 – Removal - Track from bridge

Day 8 – Preparation - Track/Girder Surfaces

Day 9 - Install - New track *

Day 10 through Day 12 – Align & Bolt Track *

Day13 – Hoist New Rall Wheel from roadway to track elevation, line bore existing supports for new wheel axle

Day 14 – Position Wheel in line with axle bore

Day 15 – Install axle

Day 16 – Testing (Monitoring components with Strain Gages should be included in the testing)

Day 17 – Perform adjustments to anchor strut and live load bearings if necessary

Day 18 – Demobilize

Move to opposite locations on bridge and repeat sequence.

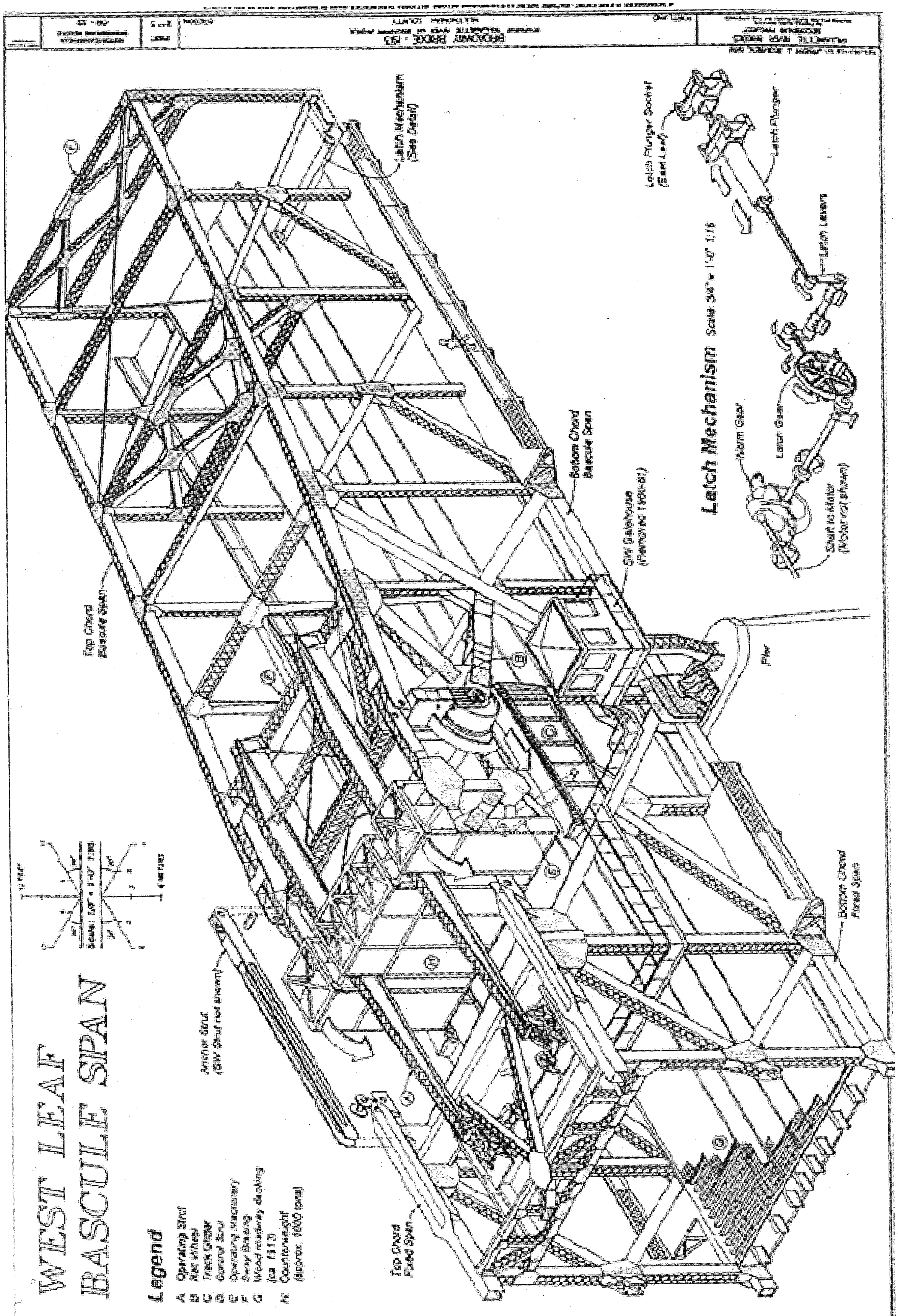
Note *: During the track replacement, perform work on the control strut simultaneously with proper bracing and supports.

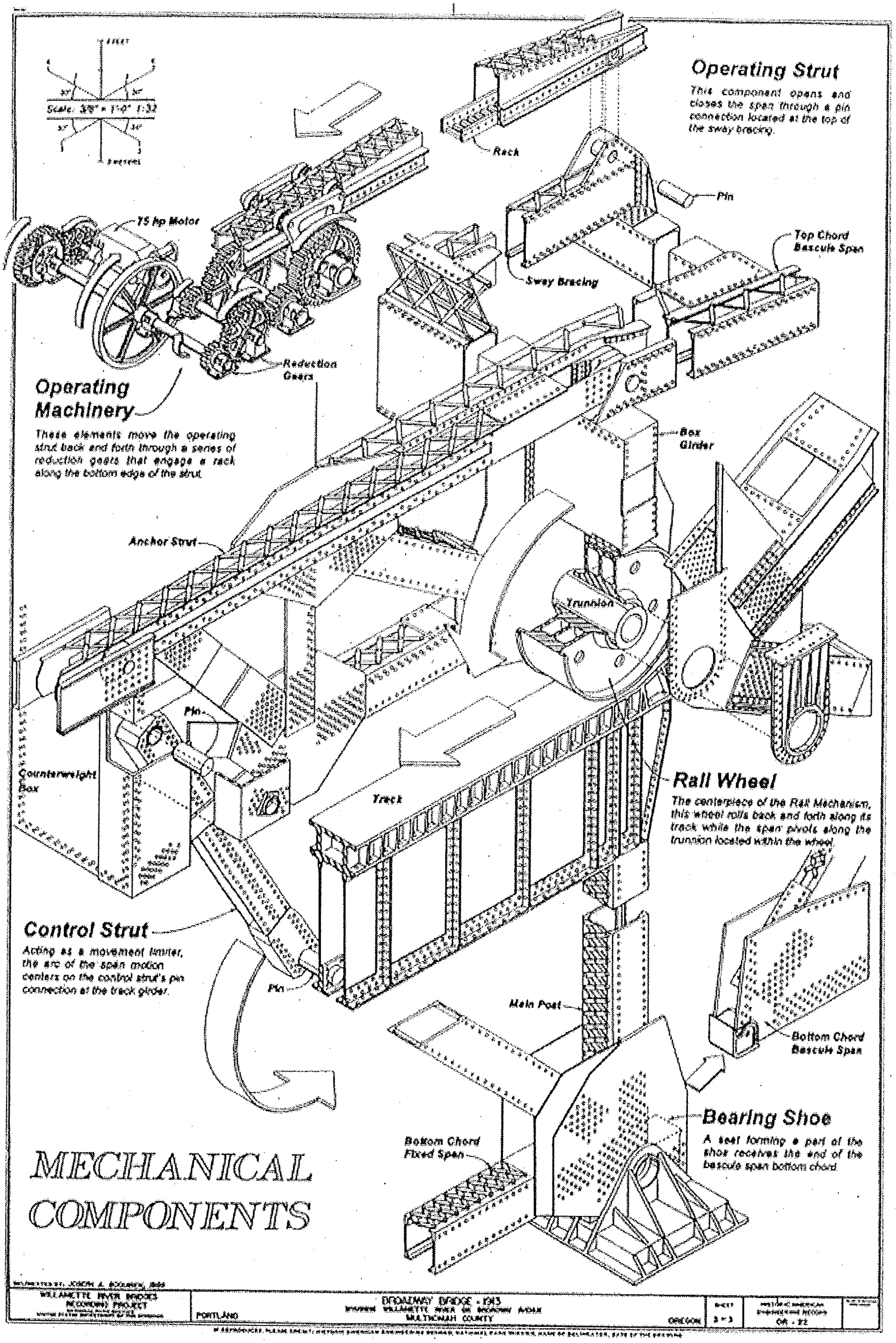
BROADWAY BRIDGE-RALL WHEEL & TRACK REPLACEMENT

BUDGETARY COST ESTIMATE

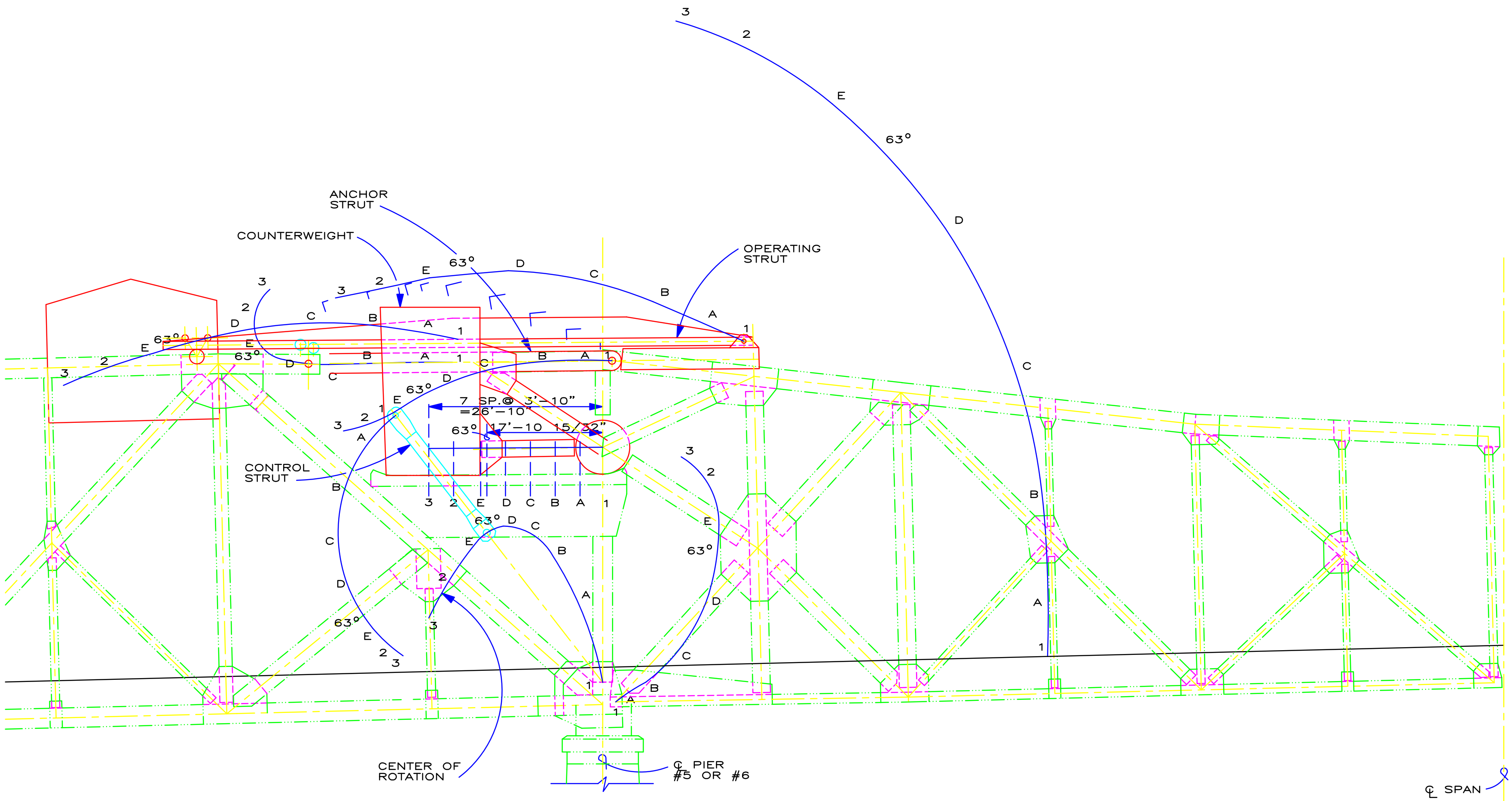
DESIGN	I.	DESIGN & PROCUREMENT OF CONTRACTOR	**$500,000**
CONSTRUCTION	II.	FABRICATE NEW WHEELS, AXLES & BEARINGS (70 KIPS) $8/LB, $560,000/EACH (x4)	$2,240,000
		FABRICATE NEW TRACKS (60 KIPS) $8/LB, $480,000/EACH (x4)	$1,920,000
		PRECISION SURVEY & REFERENCE MONUMENTS	$30,000
		WHEEL & LOAD MONITORING SYSTEM	$50,000
		CONTROL STRUT BEARINGS	$100,000
		TEMPORARY BRIDGE BRACING, JACKING & SUPPORTS	$500,000
		FIELD WORK FOR REMOVALS AND INSTALLATION OF NEW COMPONENTS (CREW OF 8 for 4 WKS/EACH LOCATION) $10,000/DAY @ 20 DAYS = 200,000 (x4)	$800,000
		CRANE (16 WKS)	$80,000
		CONSTRUCTION-SUB TOTAL	$5,720,000
		PROFIT & OVERHEAD (~21%)	$1,205,000
		CONSTRUCTION TOTAL	**$6,925,000**
CSS	III.	CONSTRUCTION SUPPORT	**$250,000**
TOTAL PROJECT		PROJECT SUB TOTAL	$7,675,000
		25% CONTINGENCY	$1,920,000
		TOTAL PROJECT BUDETARY PRICE	**$9,595,000**

APPENDIX


WEST LEAF
BASCULE SPAN
Legend
A Operating Strut
B Rail Wheel
C Track Girder
D Control Strut
E Operating Machinery
F Sway Bracing
G Wood roadway decking (ca 1913)
H Counterweight (approx. 1000 tons)
Top Chord Fixed Span
Anchor Strut (SW Strut not shown)
Top Chord Bascule Span
Bottom Chord Bascule Span
Bottom Chord Fixed Span
SW Gatehouse (Removed 1980-81)
Pier
Latch Mechanism (See Detail)
Latch Mechanism Scale: 3/4" = 1'-0" 1:16
Worm Gear
Latch Gear
Shaft to Motor (Motor not shown)
Latch Levers
Latch Plunger
Latch Plunger Socket (East Leaf)
BROADWAY BRIDGE - 1913



Att H - Bradway Rail Wheel Study
Broadway St: Willamette R (Broadway) Br Repair A/E Services



PT#	ANGLE OF MAIN SPAN OPNG.	ANGLE DIFFERANCE BETWEEN PT'S
1	CLOSED	
A	7° 33'11"	7° 33'11"
B	18° 37'44"	11° 04'33"
C	33° 37'24"	14° 59'40"
D	51° 29'21"	17° 51'37"
MAX. OPNG.	63° 00'00"	11° 30'39"
E	69° 13'57"	6° 13'57"
2	80° 06'34"	10° 52'37"
3	85° 00'52"	4° 54'18"

PT#	ANGLE OF ANCHOR STRUT	ANGLE DIFFERANCE BETWEEN PT'S
1	CLOSED	
A	180° 45'18"	10'47"
B	180° 22'43"	22'35"
C	178° 00'04"	2° 22'39"
D	170° 28'36"	7° 31'28"
MAX. OPNG.	161° 09'41"	9° 18'55"
E	154° 24'34"	6° 45'07"
2	135° 49'18"	18° 35'16"
3	117° 27'52"	18° 21'26"

PT#	ANGLE OF OPERATING STRUT	ANGLE DIFFERANCE BETWEEN PT'S
1	CLOSED	
A	2° 26'15"	2° 00'52"
B	5° 27'16"	3° 01'01"
C	9° 22'19"	3° 55'03"
D	13° 25'34"	4° 03'15"
MAX. OPNG.	14° 59'56"	1° 34'22"
E	16° 04'13"	1° 04'17"
2	17° 08'04"	1° 03'51"
3	18° 37'56"	1° 29'52"

PT#	ANGLE OF CONTROL STRUT	ANGLE DIFFERANCE BETWEEN PT'S
1	CLOSED	
A	142° 45'21"	14° 57'40"
B	160° 29'33"	17° 44'12"
C	180° 58'51"	20° 29'18"
D	202° 14'01"	21° 15'10"
MAX. OPNG.	214° 40'41"	12° 26'40"
E	219° 58'37"	5° 17'56"
2	230° 51'14"	10° 52'37"
3	235° 45'32"	4° 54'18"

APPROVED:
P.E.
BRIDGE ENGINEER
DESIGNED
DRAWN CJS
CHECKED
REVIEWED

REV	DESCRIPTION	BY	DATE

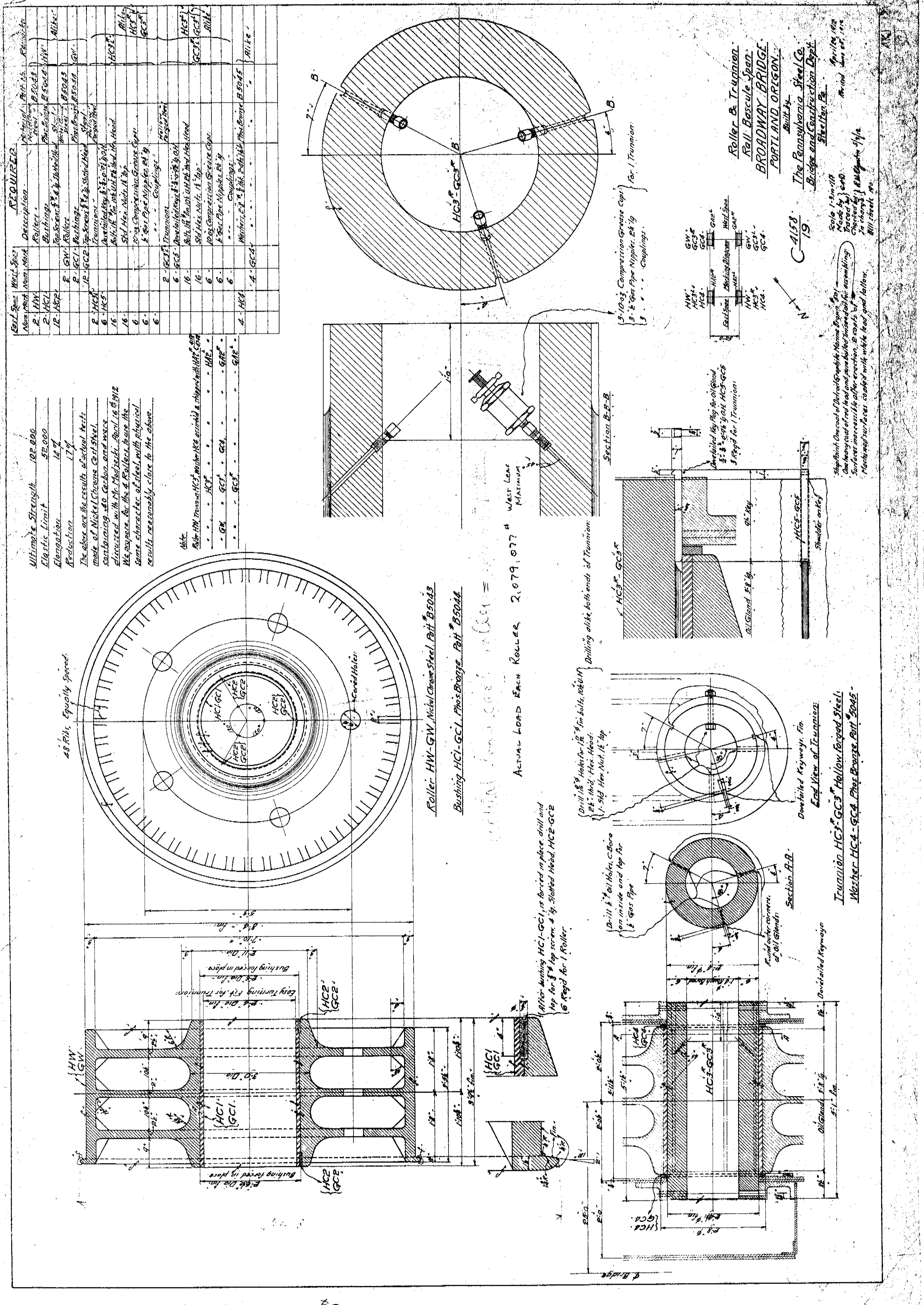
MULTNOMAH COUNTY
TRANSPORTATION DIVISION–BRIDGE SECTION

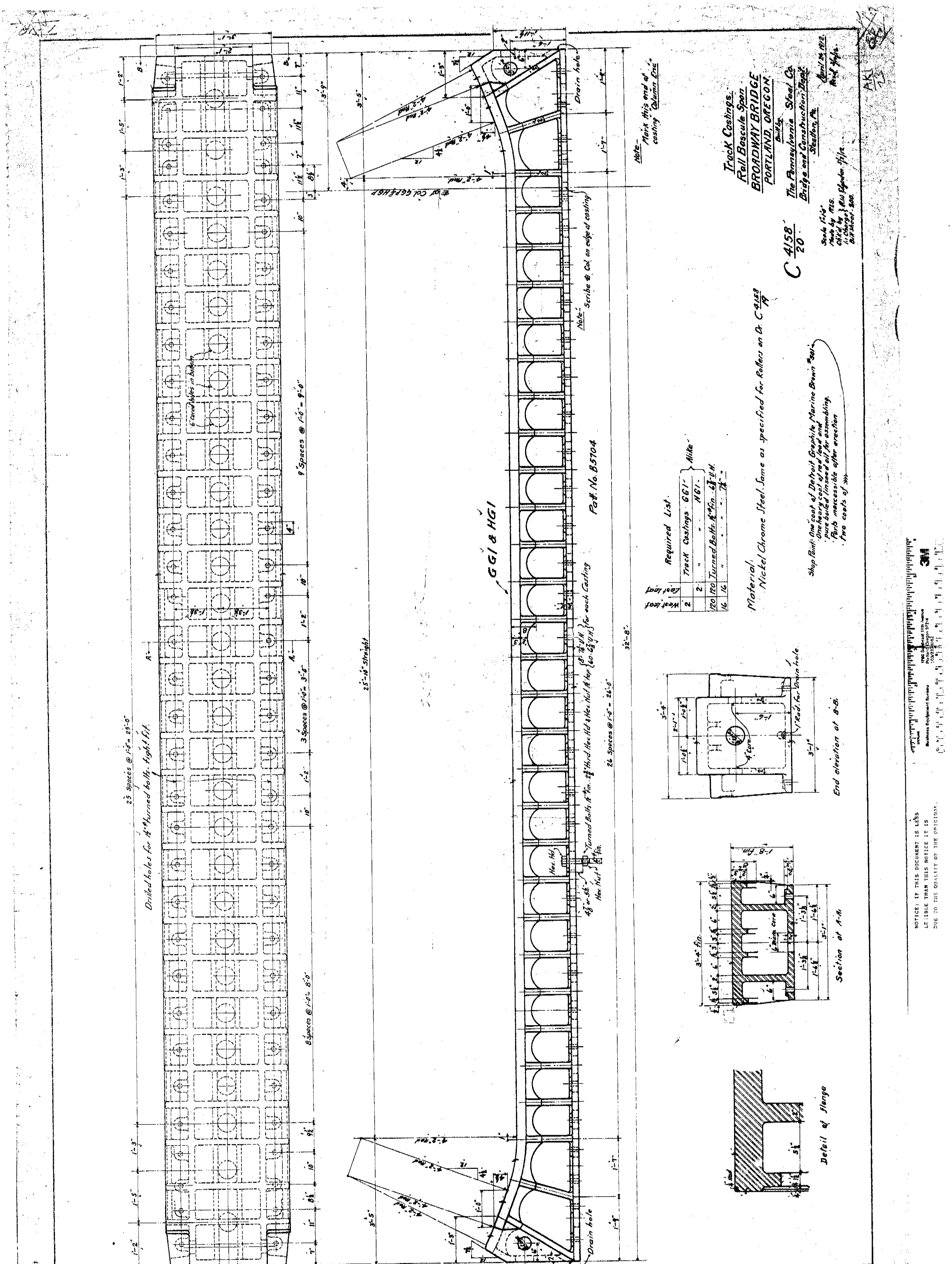
BROADWAY BRIDGE

LEAF OPENING DESIGN

DATE 1992
SCALE 1/8"=1'-0"
BRIDGE NO. 6757
FILE NO.
DRAWING NO.
SHEET OF

6757_1992_LEAF_004_LEAF OPENING DESIGN


REQUIRED
Ultimate Strength 108,000
Elastic Limit 58,000
Roller: HW-GW Nickel Chrome Steel Patt #B5043
Bushing HC1-GC1 Phos Bronze Patt #B5044
ACTUAL LOAD EACH ROLLER 2,079,077 #
Section B-B-B
Section A-A
End View of Trunnion
Trunnion HC3-GC3 Hollow forged Steel
Washer HC4-GC4 Phos Bronze Patt 5045
Roller & Trunnion
Rall Bascule Span
BROADWAY BRIDGE
PORTLAND, OREGON
Built by
The Pennsylvania Steel Co.
Bridge and Construction Dept.
Steelton, Pa.
C 4158 / 19


Track Castings.
Rail Bascule Span
BROADWAY BRIDGE
PORTLAND, OREGON.
Built by
The Pennsylvania Steel Co.
Bridge and Construction Dept.
Steelton, Pa.
April 24, 1912
C 4158/20
GG1 & HG1
Patt. No. B5704
Required List.
Track Castings GG1
Track Castings HG1
Alike
Material:
Nickel Chrome Steel Same as specified for Rollers on Dr. C 4158/19
End elevation at B-B.
Section at A-A
Detail of flange
Drain hole
25'-10" Straight
32'-8"

BROADWAY BRIDGE

Offset Measurements

Table M-1

Bridge Position	NE				Bridge Position	SE			
	Opening	Delta	Closing	Delta		Opening	Delta	Closing	Delta
0	1.219	0.000	1.219	0.000	0	0.250	0.000	0.250	0.000
15	1.188	-0.031	1.156	-0.063	15	0.469	0.219	0.438	0.188
30	1.000	-0.219	0.875	-0.344	30	0.719	0.469	0.594	0.344
45	0.813	-0.406	0.781	-0.438	45	0.969	0.719	0.906	0.656
58	0.781	-0.438	0.781	-0.438	58	1.031	0.781	1.031	0.781
Overall Travel Measured for NE = 17'-0.5"					Overall Travel Measured for SE =17'-0.25"				
Bridge Position	NW				Bridge Position	SW			
	Opening	Delta	Closing	Delta		Opening	Delta	Closing	Delta
0	40.308	0.000	40.188	-0.120	0	0.344	0.000	0.344	0.000
15	40.438	0.130	40.375	0.067	15	0.500	0.156	0.531	0.187
30	40.500	0.192	40.500	0.192	30	0.656	0.312	0.688	0.344
45	40.688	0.380	40.750	0.442	45	0.719	0.375	0.719	0.375
58	40.750	0.442	40.750	0.442	58	0.656	0.312	0.656	0.312
Overall Travel Measured for NW = 17'-0"					Overall Travel Measured for SW = 17'-4.5"				

Notes

1. The NE, SE & SW offset measurements are from outboard track edge to outboard wheel edge
2. The NW offset measurements are from inboard track edge to outboard wheel edge

BROADWAY BRIDGE
Shaft Encoder Counts
Table M-2

Test	Operation	North	South	Delta
East				
1st	Open	46176	46122	54
	Close	46166	46114	52
2nd	Open	46150	46096	54
	Close	46143	46099	44
3rd	Open	46181	46127	54
	Close	46170	46126	44
4th	Open	NR	NR	NR
	Close	NR	NR	NR
West				
Test	Operation	North	South	Delta
1st	Open	NR	NR	NR
	Close	NR	NR	NR
2nd	Open	47734	47771	37
	Close	47505	47547	42
3rd	Open	47720	47759	39
	Close	47508	47554	46
4th	Open	47668	47730	62
	Close	47507	47552	45

Note:
1. NR = Not Recorded
2. There are 1000 counts per shaft revolution

Broadway Bridge Rall Wheel Rolling Contact Fatigue Investigation

Objective:
Identify the investigative approaches that are suitable to determine the service life and current condition of the Rall wheel track and wheel cast steel structures?

Summary:
Some light, carbon-like flakes have been observed during the past month on the Rall wheel track, and the surface morphology of the Rall wheel and track have pitting/spalling features that may be a result of rolling contact fatigue. The spalling features have been present for many years, but the pitting and carbon like flakes appear to be a more current development, or one that has recently been observed.

The Rall wheel track has not always been kept clean during operations, and the Rall wheel has rolled over many types of debris in the past including: screws, keys, pipes, sand and probably other objects too.

In the 1980's the Rall wheels formed large through cracks several feet long around the circumference of the wheel. These cracks were weld repaired in accordance to a repair procedure designed by metallurgists and engineers from MEI Charlton. Most of the rolling surface of the Rall wheel is warped, probably due to the weld repairs, thus, an even load distribution is unlikely.

The frequency of Broadway Bridge openings is once per week, since the year 1913. Each opening operation requires approximately one Rall wheel rotation to the full open position.

Wheel Dimensions
Diameter, D_{rall}, = 100 inches
Width, w_{rall}, = 40 inches

Load per Rall wheel (two Rall wheels/tracks per bascule):
L_{rall} = 2E06 lbs

Brinell Hardness Rall Wheel and Track Test Results in year 2005
NE
Wheel face = 243
Wheel side = 218
Used track = 238
Unused track = 224

NW
Wheel face = 256
Wheel side = 231
Used track = 263
Unused track = 213

According to 26th edition of Machinery's Handbook, fig 2 page 474, the 213 Brinell number graphically shows a yield strength range of 67% to 85% of the tensile strength of 107ksi, which equates to a yield strength range of 71.7 to 91 ksi.

KOON-HALL-ADRIAN METALLURGICAL

KHAMETAL.COM

5687-A S.E. International Way, Portland, Oregon 97222

PHONE: 503-653-2904
FAX: 503-653-9591

CUSTOMER SAMPLE DESCRIPTION

CUSTOMER	MULTNOMAH COUNTY OREGON — PAGE 1 of 2
ORDER NUMBER	P.O. VERBAL
SPECIFICATION	ASTM A370-03a
TEST DESCRIPTION	ROOM TEMPERATURE TENSILE & CHARPY IMPACT TEST
MATERIAL IDENTITY	STEEL; BROADWAY BRIDGE CASTING; WEB SECTION

DATE 12/2/2004 WORK ORDER 99551

THIS CERTIFICATE SHALL NOT BE REPRODUCED EXCEPT IN FULL, WITHOUT OUR WRITTEN APPROVAL - SEE REVERSE SIDE FOR STATEMENT OF WARRANTIES

CERTIFICATION

LABORATORY NUMBER	UTS (psi)	0.2% OFFSET Y.S. (psi)	ELONGATION IN 4D (%)	REDUCTION OF AREA (%)	TEMP°F	DIRECTION
K17556-1	108,000	52,800	12.0	14.0	ROOM	LONG DIRECTION @ 1/4 THK

ANOMALY @ FRACTURE

ORIGINAL SPECIMEN AREA 0.1987 in^2

V-NOTCH CHARPY IMPACT TEST

	SIZE (mm)	FT.-LBS.	TEMP°F	DIRECTION
K17556-3	10 x 10	≈2.0	+40	LONG DIRECTION @ 1/4 THICKNESS
K17556-4	10 x 10	≈2.5	+40	LONG DIRECTION @ 1/4 THICKNESS
K17556-5	10 x 10	≈2.5	+40	LONG DIRECTION @ 1/4 THICKNESS
AVERAGE		≈2.5		

PER ASTM E23-02a, ANNEX A2, PARAGRAPH A2.4.3, IMPACT VALUES OUTSIDE OUR MACHINE'S VERIFIED RANGE OF 12.5 TO 211.0 FT-LBS ARE APPROXIMATE AND ARE REPORTED FOR INFORMATION ONLY.

NO SPECIFIED REQUIREMENTS, VALUES FOR INFORMATION ONLY

THE RECORDING OF FALSE, FICTITIOUS, OR FRAUDULENT STATEMENTS OR ENTRIES ON THIS CERTIFICATE MAY BE PUNISHED AS A FELONY UNDER FEDERAL LAW.

NADCAP PRI PERFORMANCE REVIEW INSTITUTE - Accredited KHA-101D

MATERIAL TESTING LABORATORY

KOON HALL ADRIAN METALLURGICAL

ISO/IEC 17025 CERTIFIED

BY Robert L. Adrian

ROBERT ADRIAN, Q.A. MANAGER / SHAUN HUEY, Q.C. MANAGER

ADRIAN METALLURGICAL OREGON OFFICIAL SEAL

2 KHA

KOON-HALL-ADRIAN METALLURGICAL
KHAMETAL.COM
5687-A S.E. International Way, Portland, Oregon 97222
PHONE: 503-653-2904
FAX: 503-653-9591

CUSTOMER SAMPLE DESCRIPTION

CUSTOMER	MULTNOMAH COUNTY OREGON	PAGE 2 of 2
ORDER NUMBER	P.O. VERBAL	
SPECIFICATION	NONE	
TEST DESCRIPTION	CHEMISTRY	
MATERIAL IDENTITY	STEEL; BROADWAY BRIDGE CASTING; WEB SECTION	

DATE 12/2/2004 WORK ORDER 99551

THIS CERTIFICATE SHALL NOT BE REPRODUCED EXCEPT IN FULL, WITHOUT OUR WRITTEN APPROVAL - SEE REVERSE SIDE FOR STATEMENT OF WARRANTIES

CERTIFICATION

LABORATORY NUMBER	CHEMISTRY (%) K17556-2
CARBON	0.43
MANGANESE	0.82
PHOSPHORUS	0.032
SULFUR	0.040
SILICON	0.17
CHROMIUM	0.59
NICKEL	1.40
MOLYBDENUM	<0.01
COPPER	0.18
IRON	BALANCE

ANALYTICAL FACILITY: STORK MATERIALS TESTING & INSPECTION
15062 BOLSA CHICA, HUNTINGTON BEACH, CA 92649

NO SPECIFIED REQUIREMENTS, VALUES FOR INFORMATION ONLY

THE RECORDING OF FALSE, FICTITIOUS, OR FRAUDULENT STATEMENTS OR ENTRIES ON THIS CERTIFICATE MAY BE PUNISHED AS A FELONY UNDER FEDERAL LAW.

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KOON HALL ADRIAN METALLURGICAL
ISO/IEC 17025 CERTIFIED
KHA-101D

BY Robert L. Adrian

ROBERT ADRIAN, Q.A. MANAGER / TRINA KOGLE, Q.C. MANAGER

2 KHA

M-001 NW wheel & track

M-002 NW wheel upper portion

M-003 NW wheel lower portion

M-004 NW wheel defect

M-005 NW wheel defect

M-006 NW wheel defect

M-007 NW wheel defect

M-008 NW wheel defect

M-009 NW wheel defect

M-010 NW wheel defect

M-011 NW wheel defect

M-012 NW wheel

M-013 NW wheel

M-014 NW wheel rim defect

M-015 NW wheel (bridge open)

M-016 NW wheel rim defect (bridge open)

M-017 NW track

M-018 NW track defect

M-019 NW track defect

M-020 NW track defect, start

M-021 NW track defect, finish

M-022 NW track defect

M-023 NW track (bridge open)

M-024 SW wheel & track

M-025 SW wheel upper portion

M-026 SW wheel defect


M-027 SW wheel lower portion


M-028 SW wheel defect

M-029 SW wheel

M-030 SW wheel (bridge open)


M-031 SW wheel (bridge open)


M-032 SW track

M-033 SW track

M-034 SW track

M-035 SW track


M-036 SW track (bridge open)

M-037 NE wheel & track

M-038 NE wheel

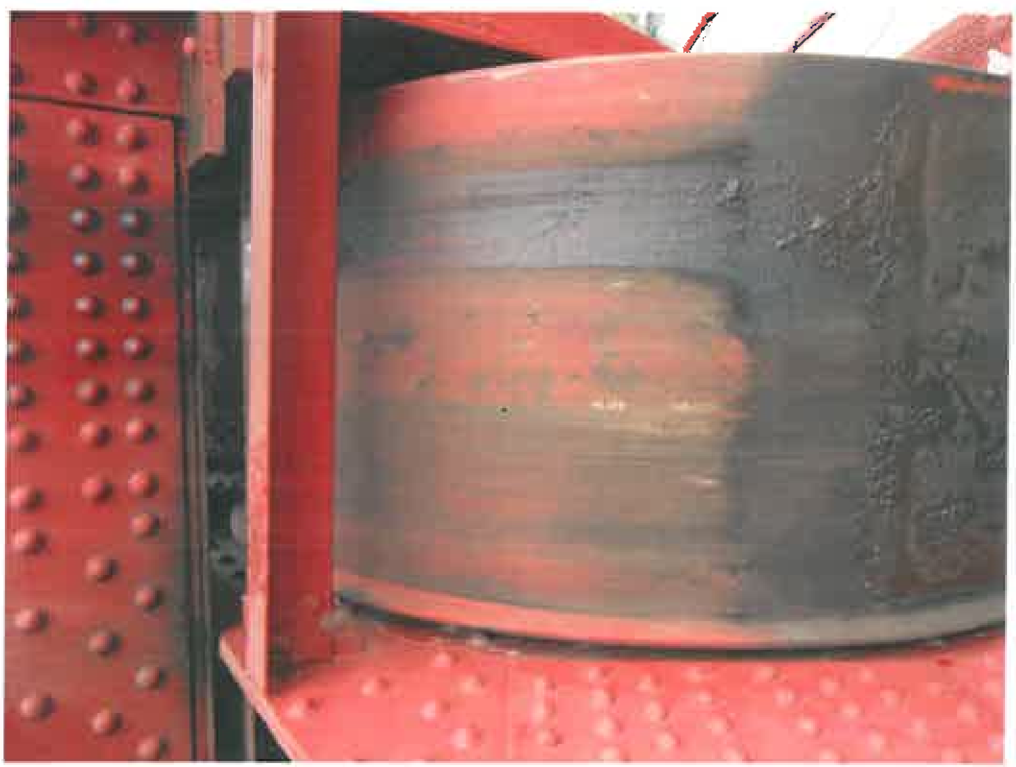
M-039 NE wheel defect

M-040 NE wheel defect

M-041 NE wheel (bridge open)

M-042 NE wheel defect (bridge open)

M-043 NE wheel (bridge open)



M-044 NE wheel (bridge open)

M-045 NE wheel defect (bridge open)

M-046 NE track

M-047 NE track (bridge open)

M-048 SE wheel & track

M-049 SE wheel upper portion

M-050 SE wheel lower portion

M-051 SE wheel defect

M-052 SE wheel defect


M-053 SE wheel (bridge open)


M-054 SE wheel (bridge open)

M-055 SE wheel defect (bridge open)

M-056 SE wheel defect (bridge open)

M-057 SE track

M-058 SE unused track

M-059 SE track crack

M-060 SE track crack

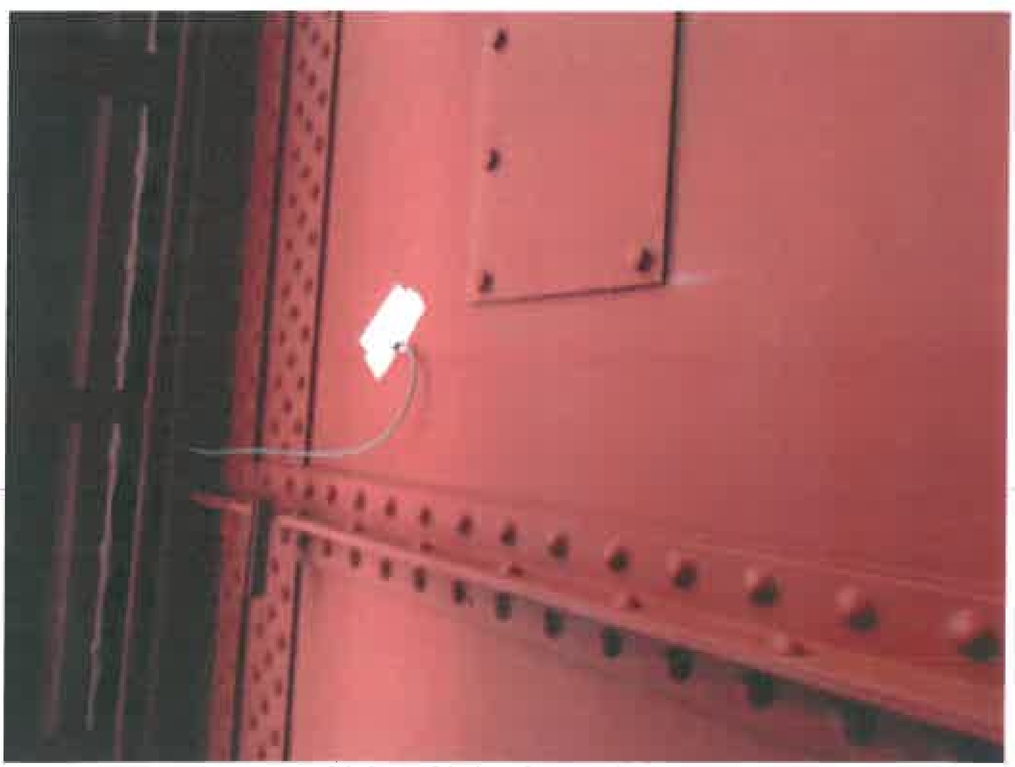
M-061 SE track

M-062 SE track


M-063 SE track (bridge open)


M-064 Column Strain Gage

M-065 Control Strut Strain Gage



M-066 Girder Strain Gage


M-067 Shaft Strain Gages


M-068 Column Length Change

M-069 Rail Wheel Travel Encoder


M-070 Machinery Shaft Encoder

M-071 Track Inclinometers

Figure 1 SW OP strut rubbing inboard side at pin. Note grease smeared on metal to metal wearing surface.


Figure 2 NW OP strut at pinned area 'not' showing rubbing like the SW strut.

Figure 3 Typical wear on Anchor Strut rub block.

Figure 4 Bolt failure location on Anchor Strut reinforcement plate near Anchor Strut pin.

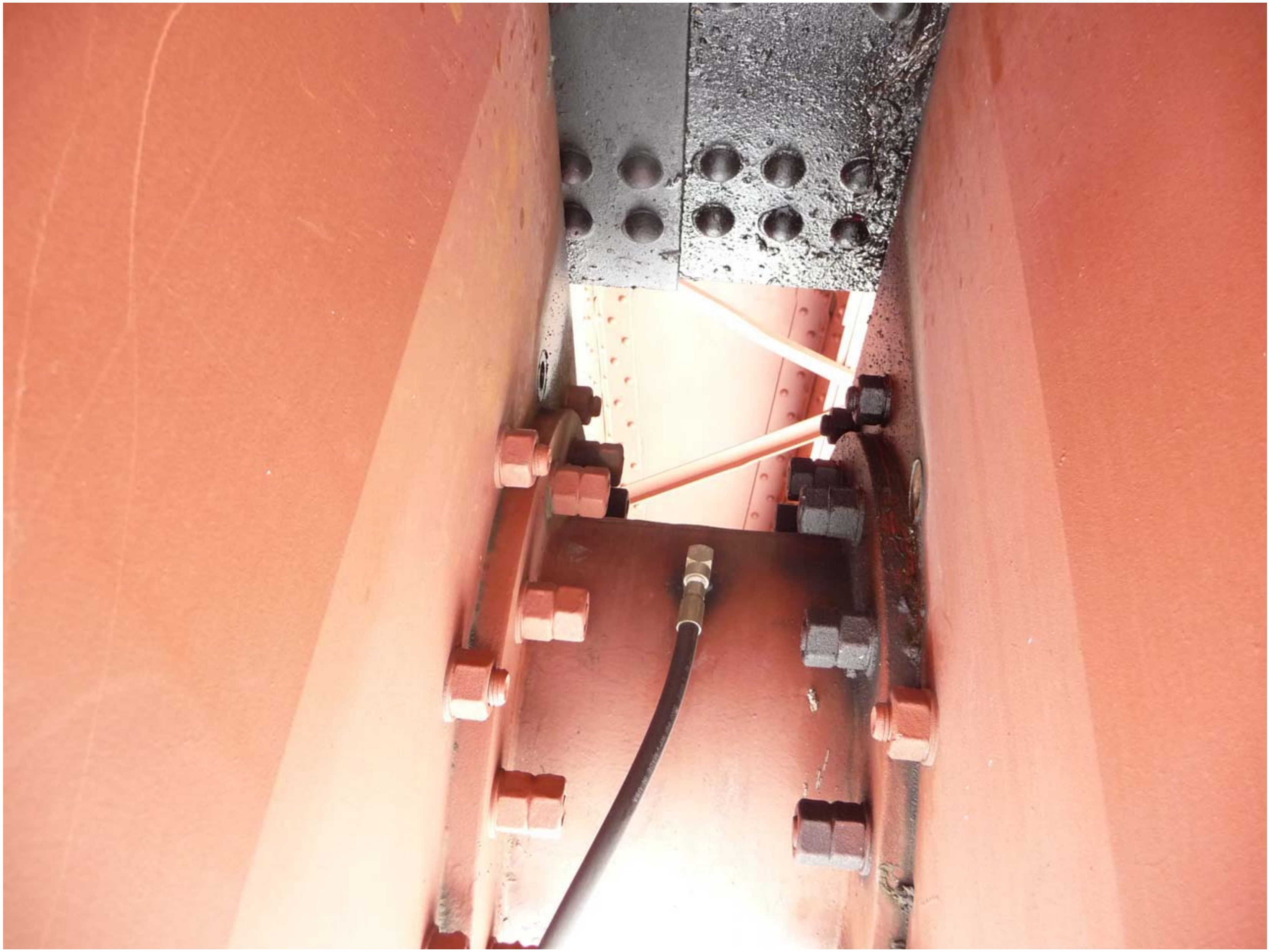


Figure 5 Another Anchor Strut view of locations where bolts broke near Anchor Strut pin.

BROADWAY BRIDGE RALL WHEEL STUDY

Volume II

November 2012

Client: CH2M Hill, Inc.

Owner: Multnomah County, OR

Broadway Bridge Rall Wheel Study

November 2012

Table of Contents

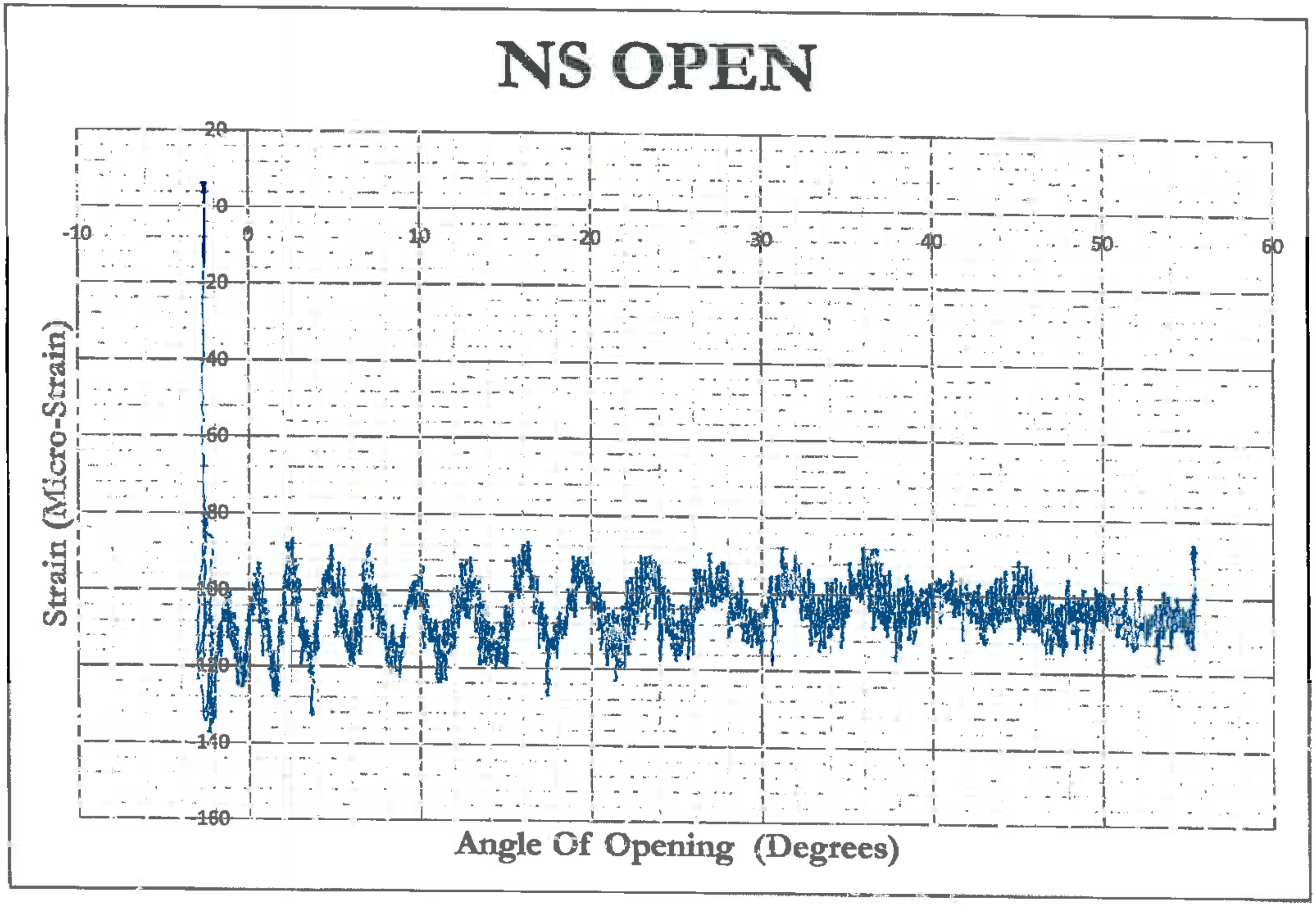
Volume I

Volume II

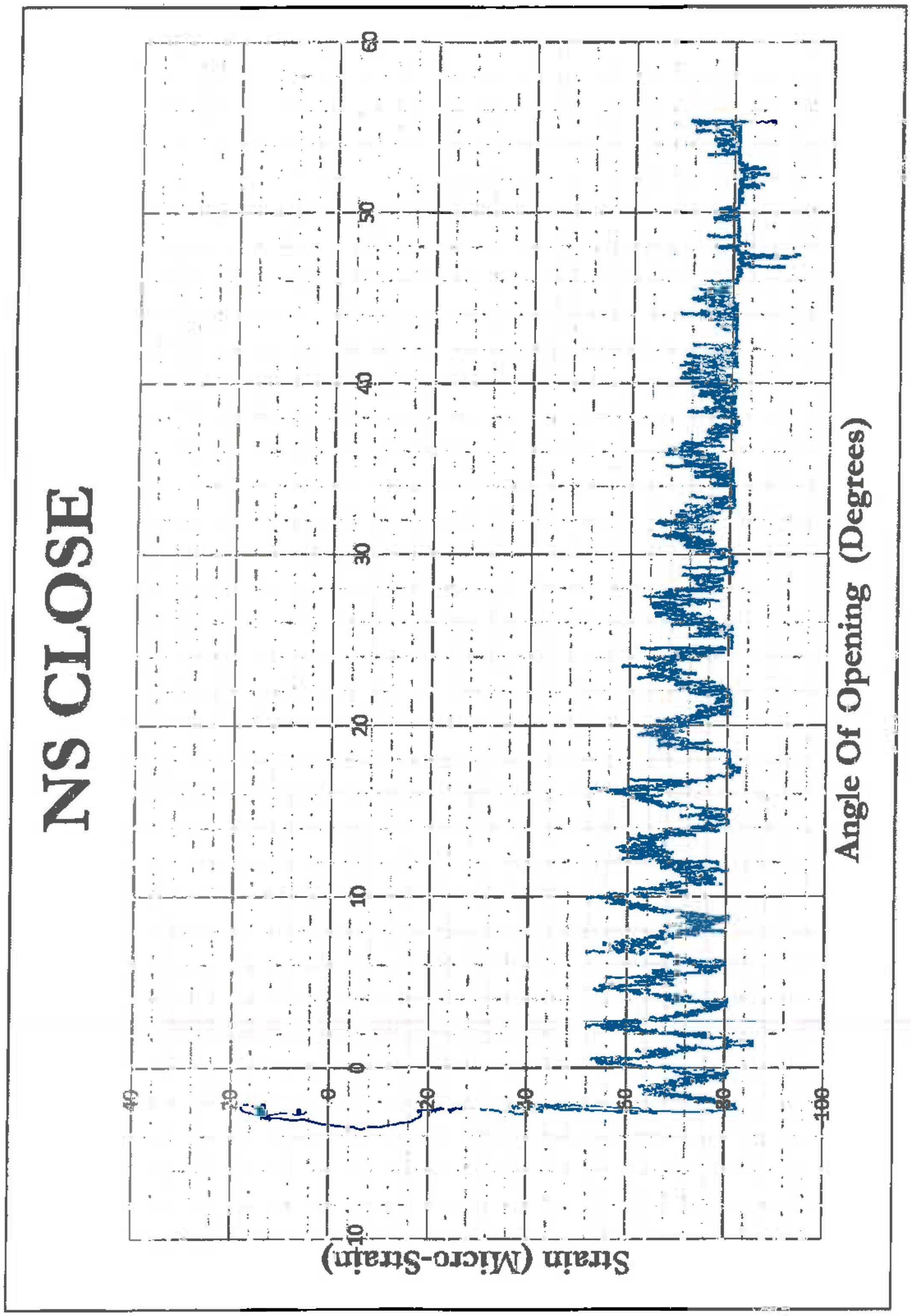
Legend for Graphs

“OPEN”	Bridge Opening
“CLOSE”	Bridge Closing
“NS”	North Machinery Shaft (Strain Gage)
“SS”	South Machinery Shaft (Strain Gage)
“A1N”	Rall Wheel Track Column - North (Strain Gage)
“A1S”	Rall Wheel Track Column - South (Strain Gage)
“A2IN”	Control Strut Inboard - North (Strain Gage)
“A2ON”	Control Strut Outboard - North (Strain Gage)
“A2IS”	Control Strut Inboard - South (Strain Gage)
“A2OS”	Control Strut Outboard - South (Strain Gage)
“A3IHN”	Track Girder Inboard Horizontal - North (Strain Gage)
“A3IVN”	Track Girder Inboard Vertical - North (Strain Gage)
“A3OHN”	Track Girder Outboard Horizontal - North (Strain Gage)
“A3OVN”	Track Girder Outboard Vertical - North (Strain Gage)
“A3IHS”	Track Girder Inboard Horizontal - South (Strain Gage)
“A3IVS”	Track Girder Inboard Vertical - South (Strain Gage)
“A3OHS”	Track Girder Outboard Horizontal - South (Strain Gage)
“A3OVS”	Track Girder Outboard Vertical - South (Strain Gage)
“RAISE”	Bridge Opening
“LOWER”	Bridge Closing
“NE L/R“	North-East Left/Right (Rall Wheel Track-Transverse Inclinometer)
“NE F/B”	North-East Front/Back (Rall Wheel Track-Longitudinal Inclinometer)
“SE L/R“	South-East Left/Right (Rall Wheel Track-Transverse Inclinometer)
“SE F/B”	South-East Front/Back (Rall Wheel Track-Longitudinal Inclinometer)
“NW L/R“	North-West Left/Right (Rall Wheel Track-Transverse Inclinometer)
“NW F/B”	North-West Front/Back (Rall Wheel Track-Longitudinal Inclinometer)
“SW L/R“	South-West Left/Right (Rall Wheel Track-Transverse Inclinometer)
“SW F/B”	South-West Front/Back (Rall Wheel Track-Longitudinal Inclinometer)

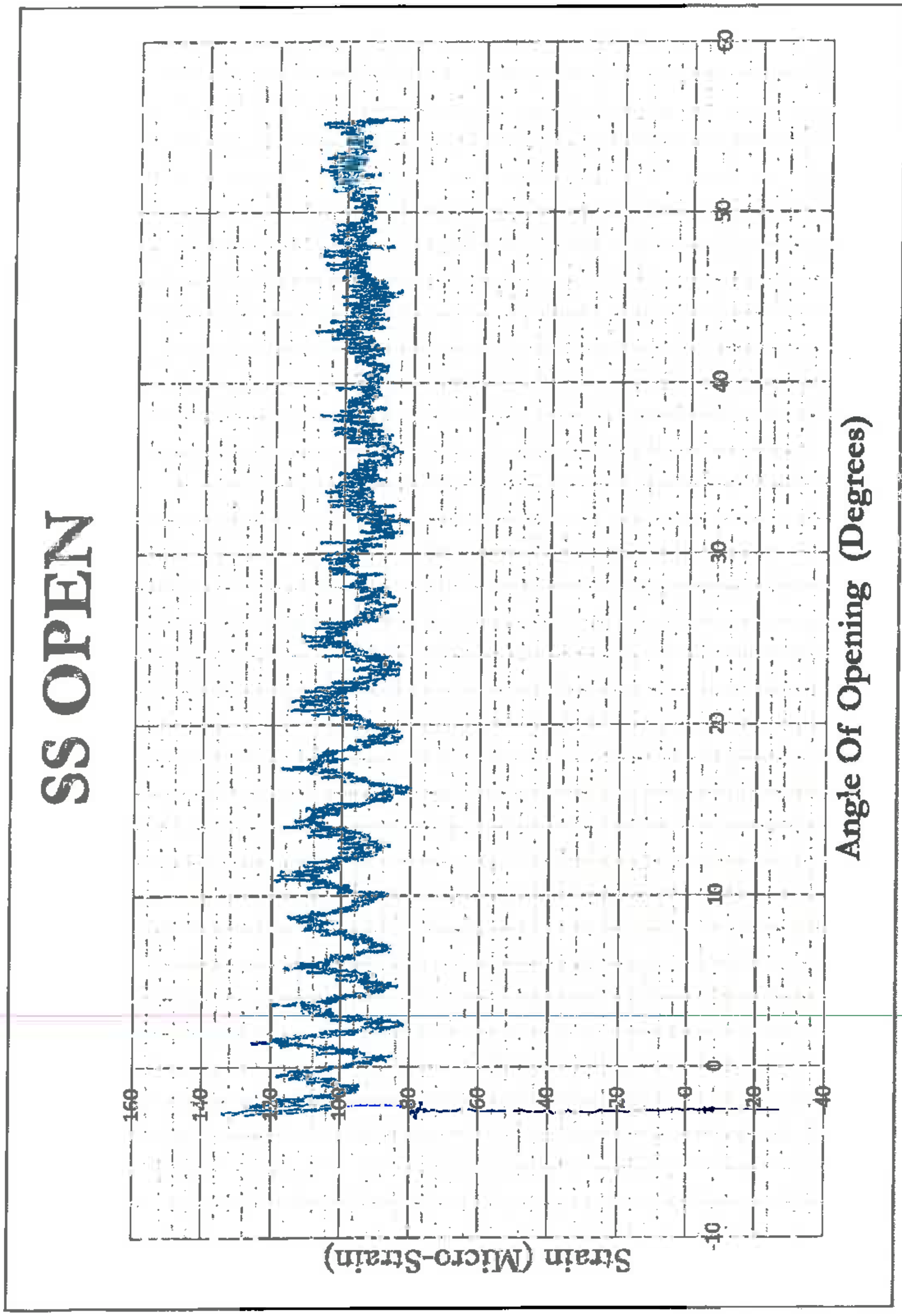
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



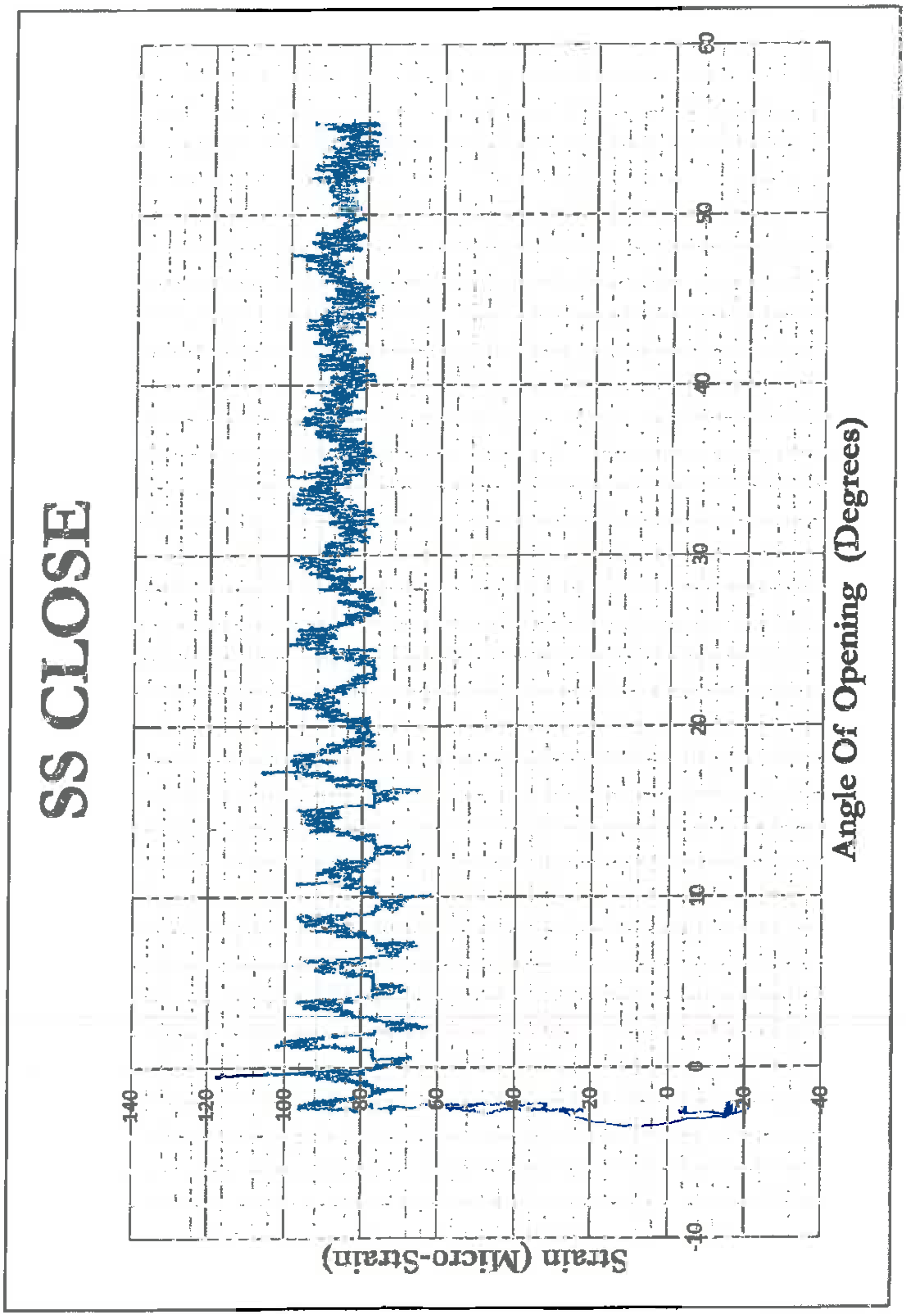
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



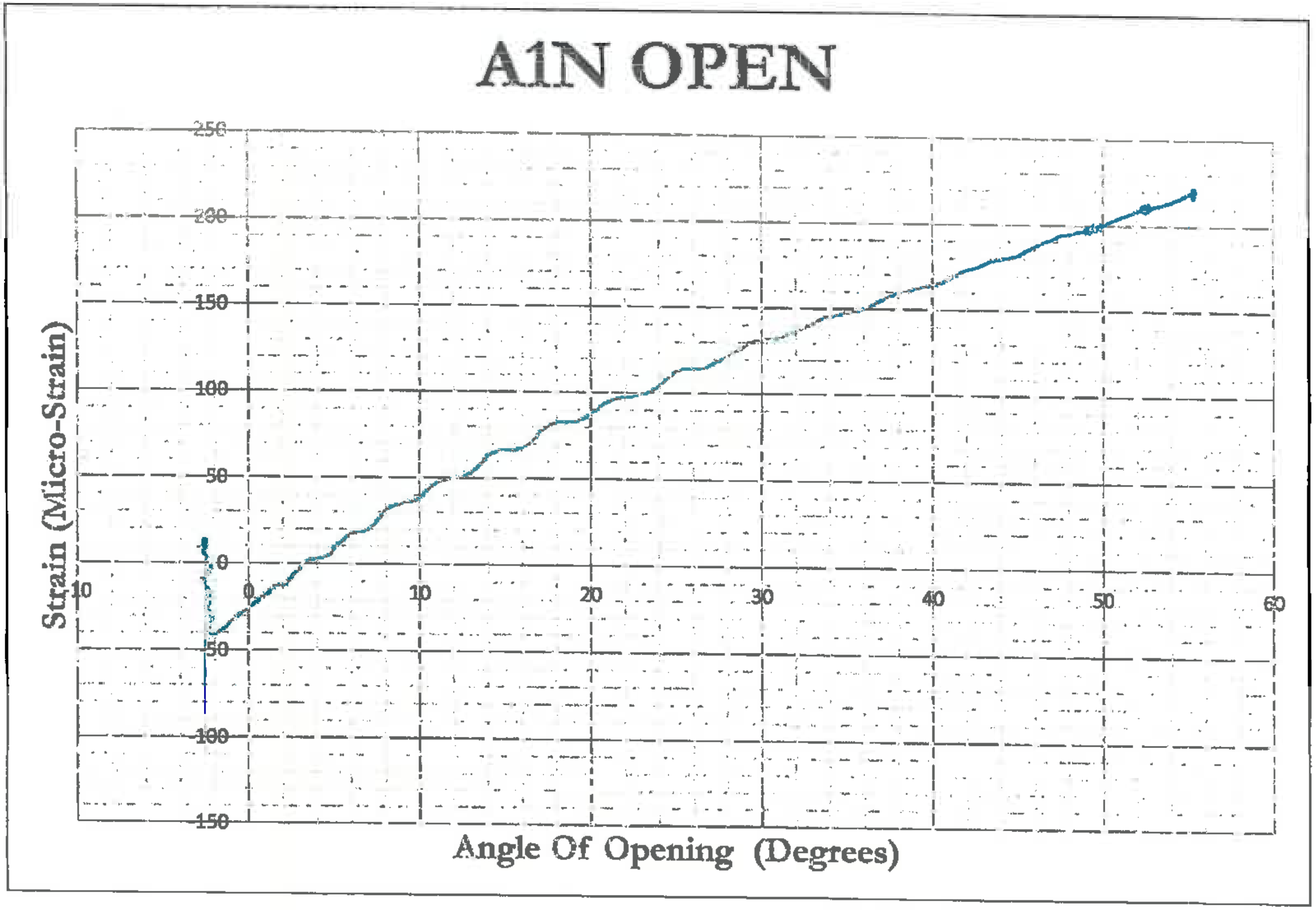
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



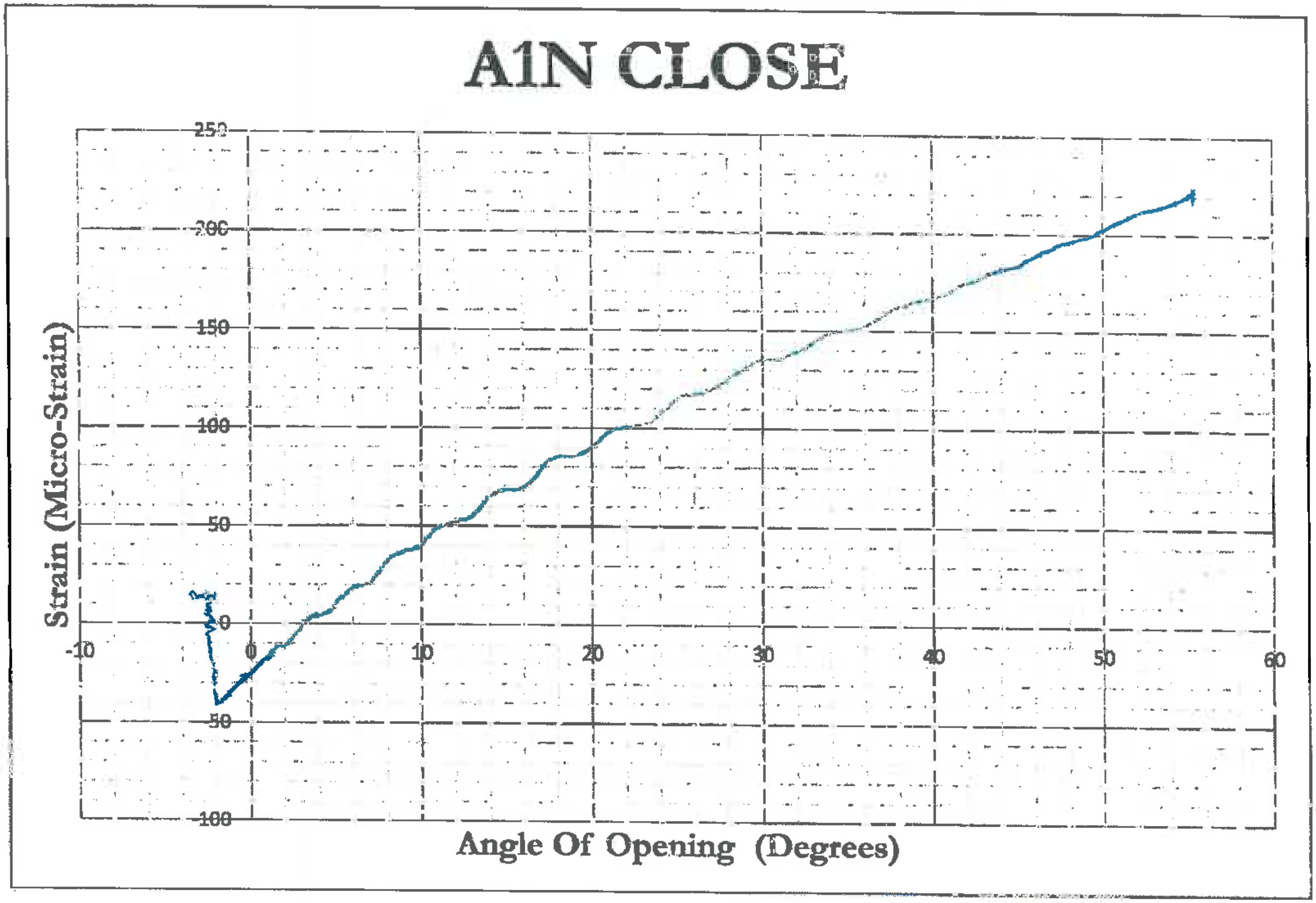
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



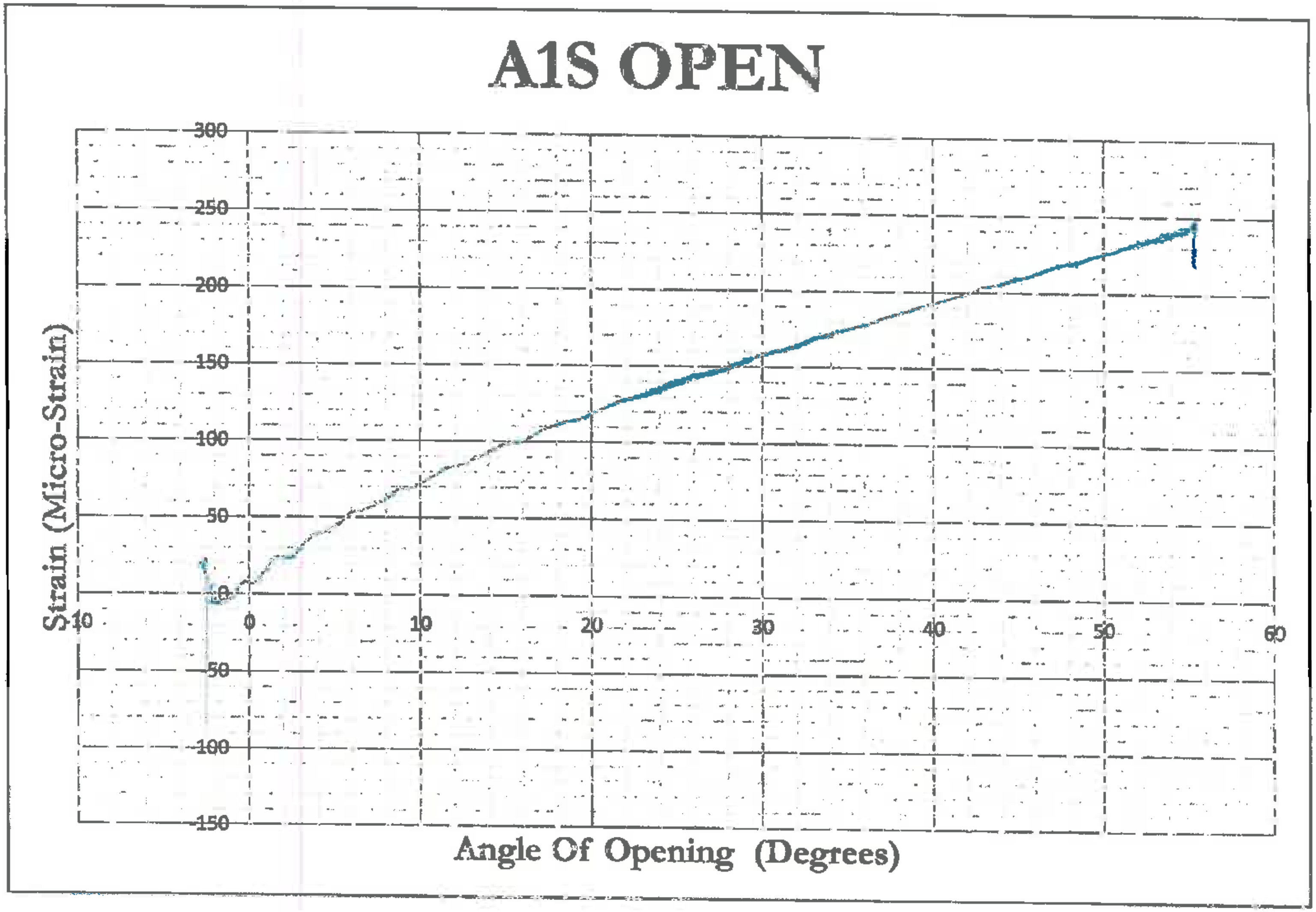
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



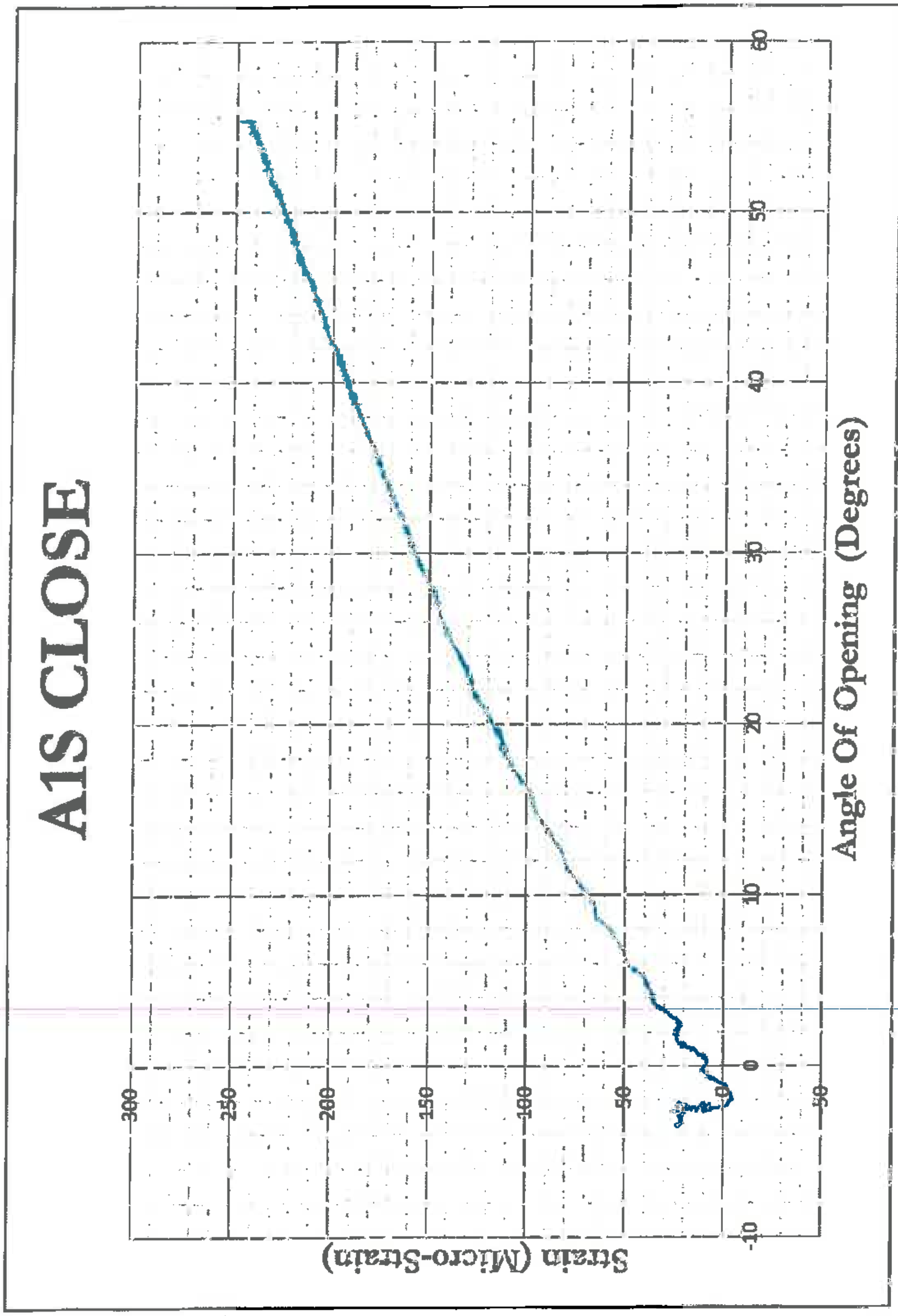
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



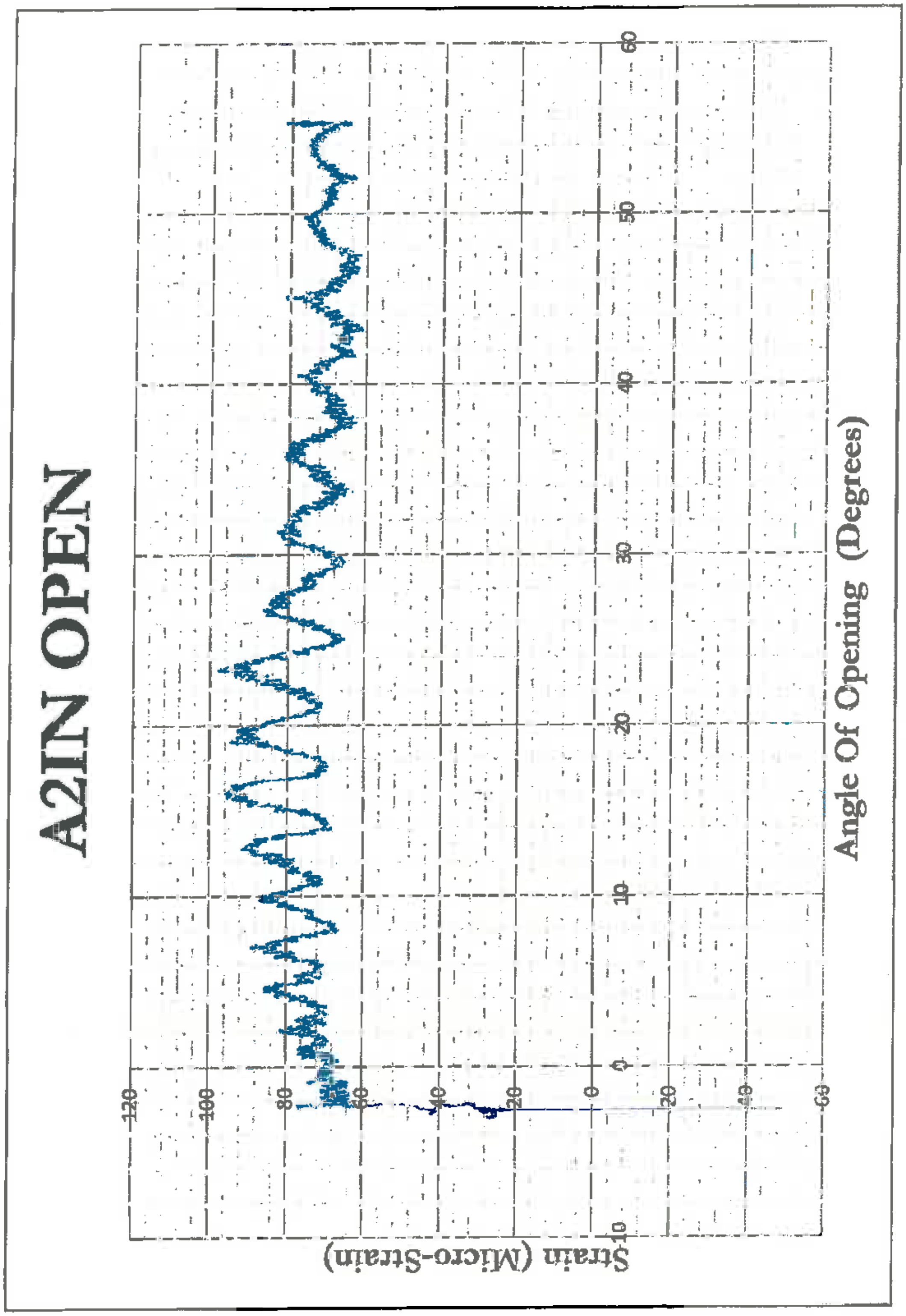
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



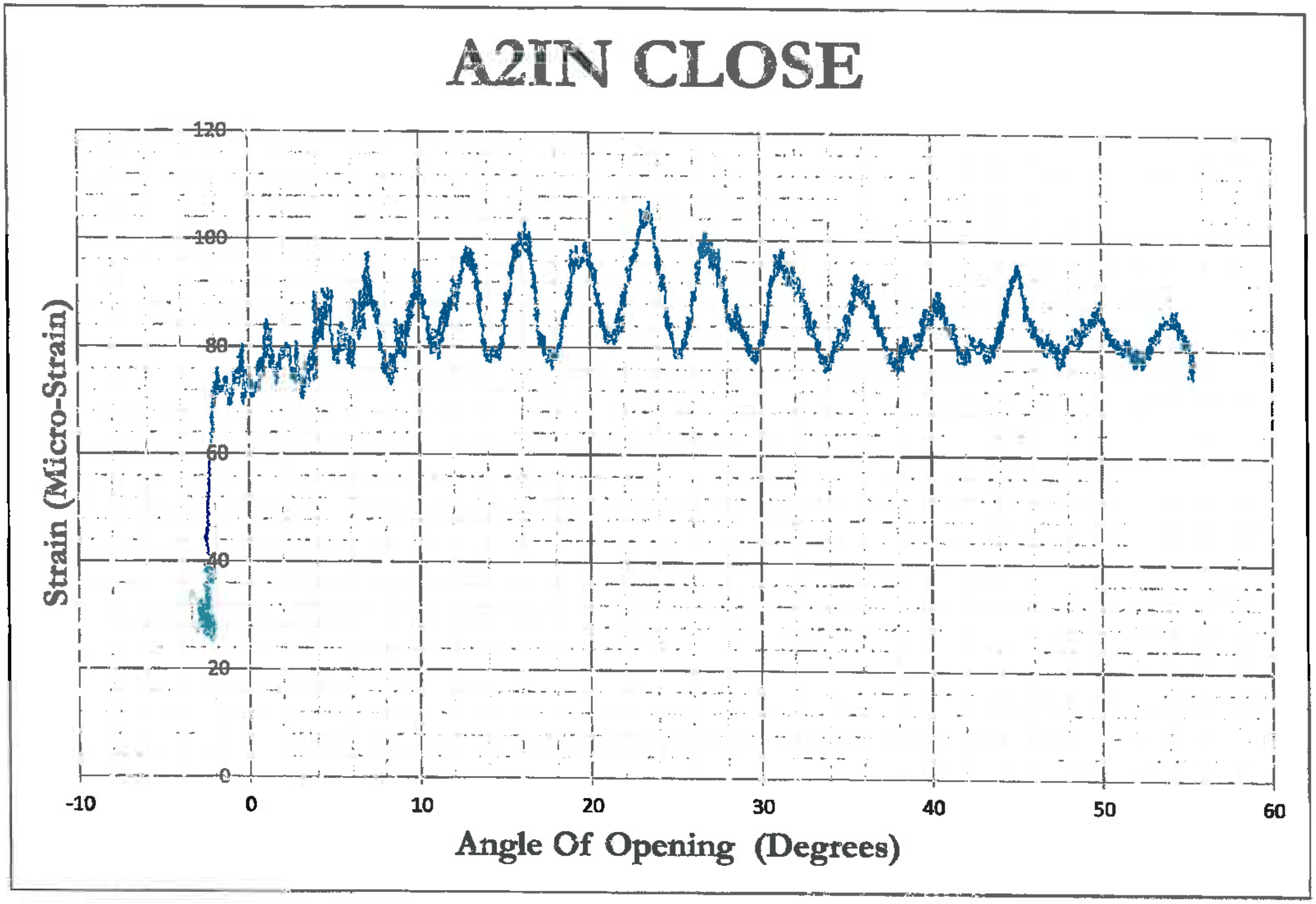
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



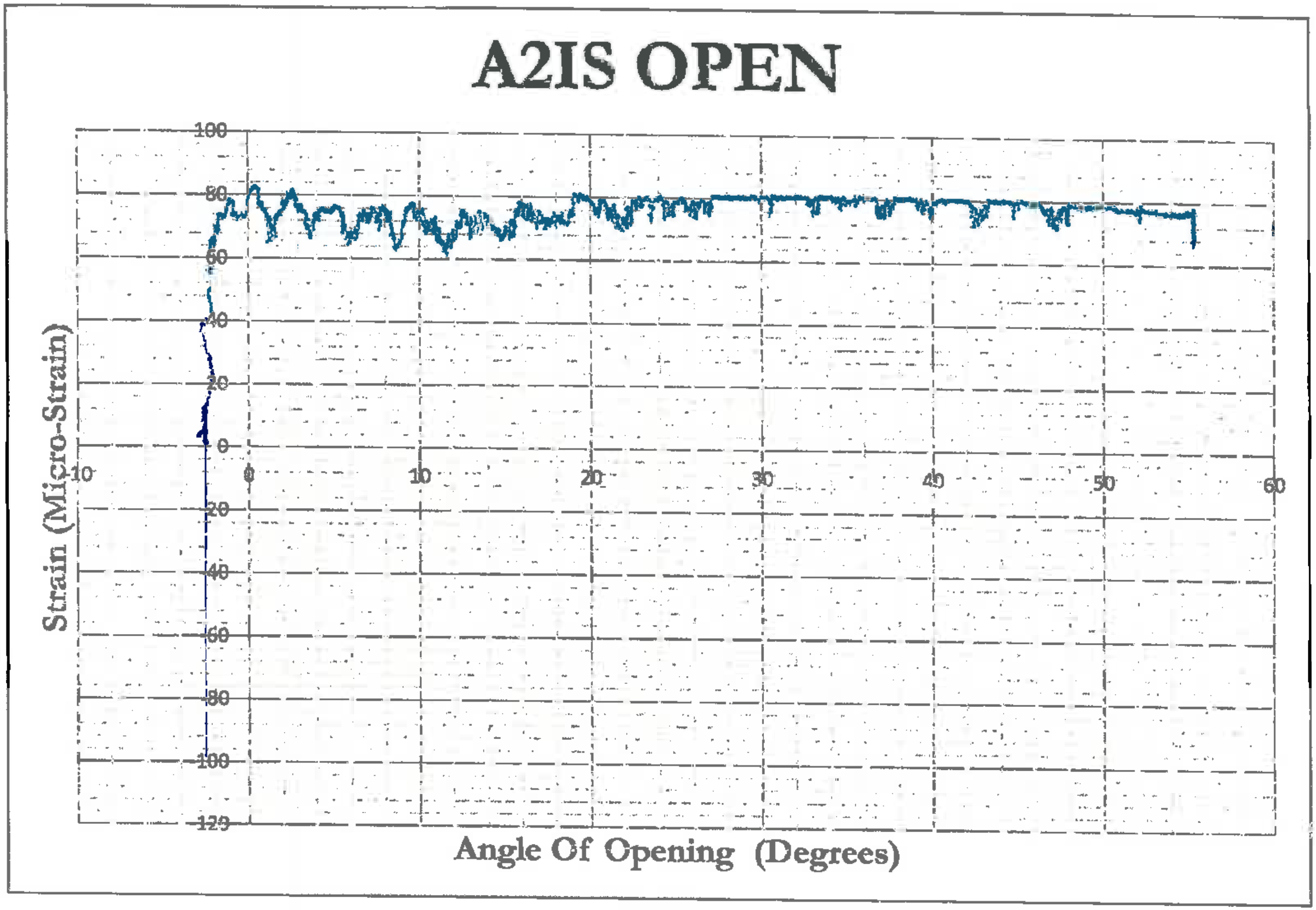
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3

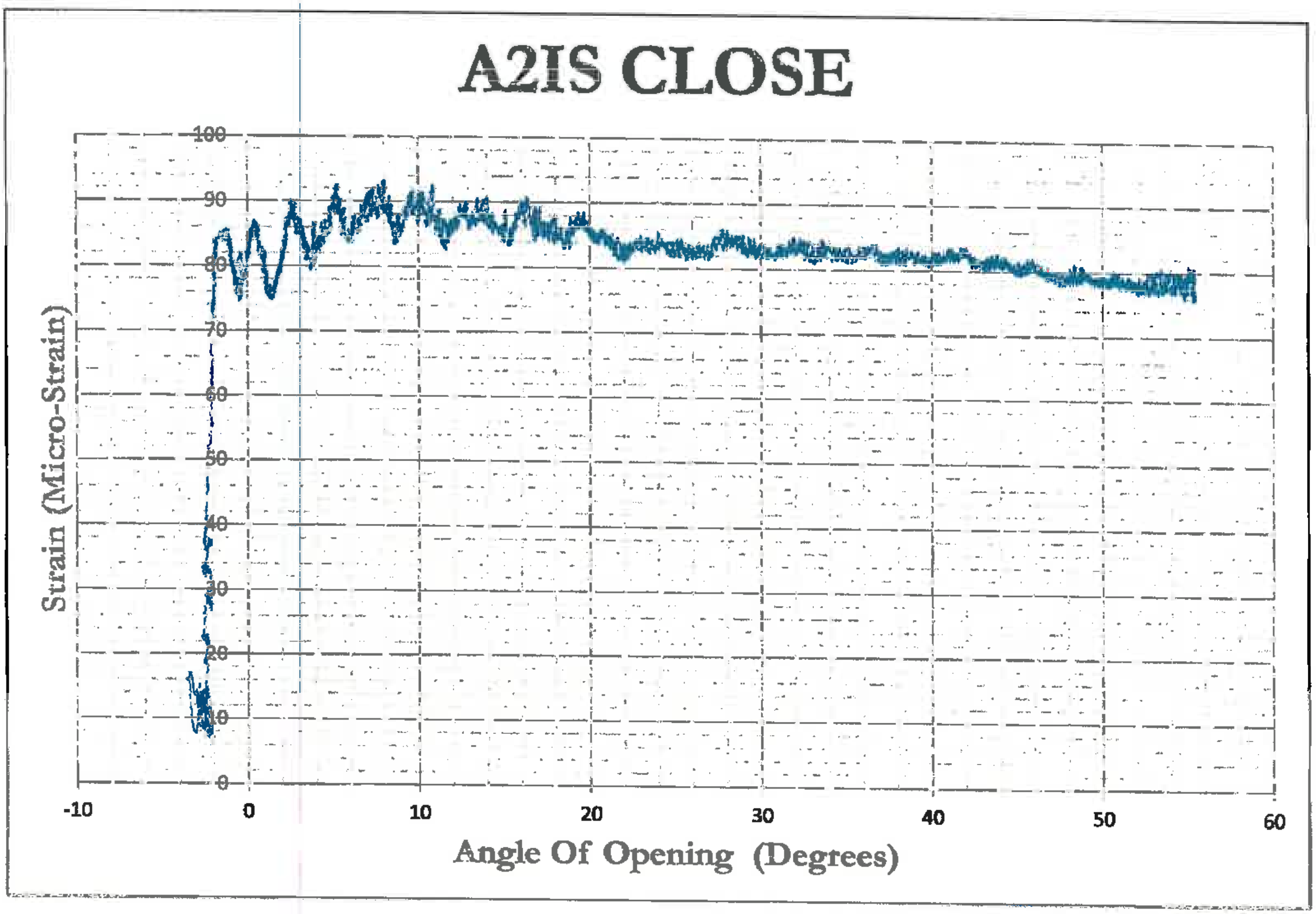


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3

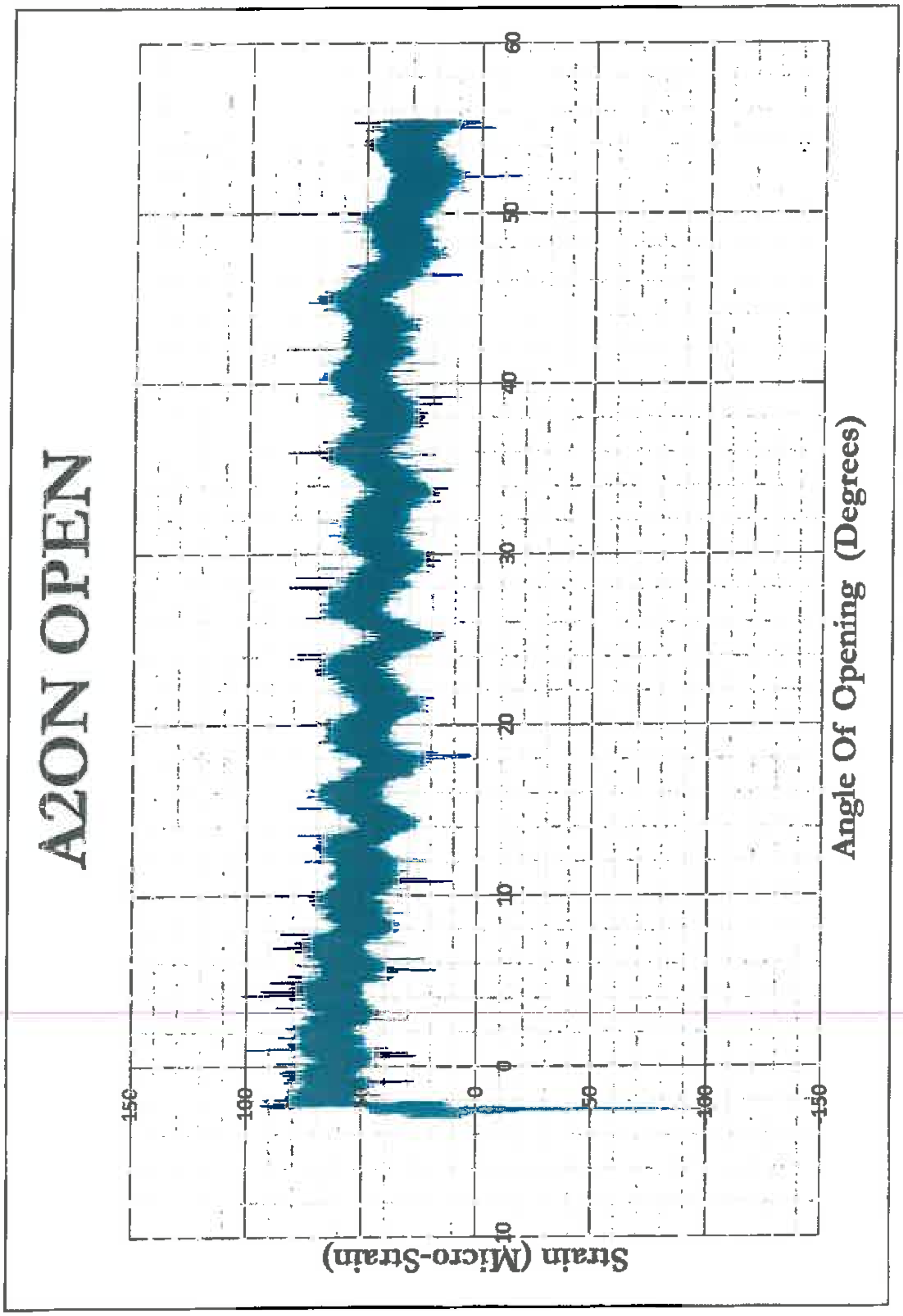


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3

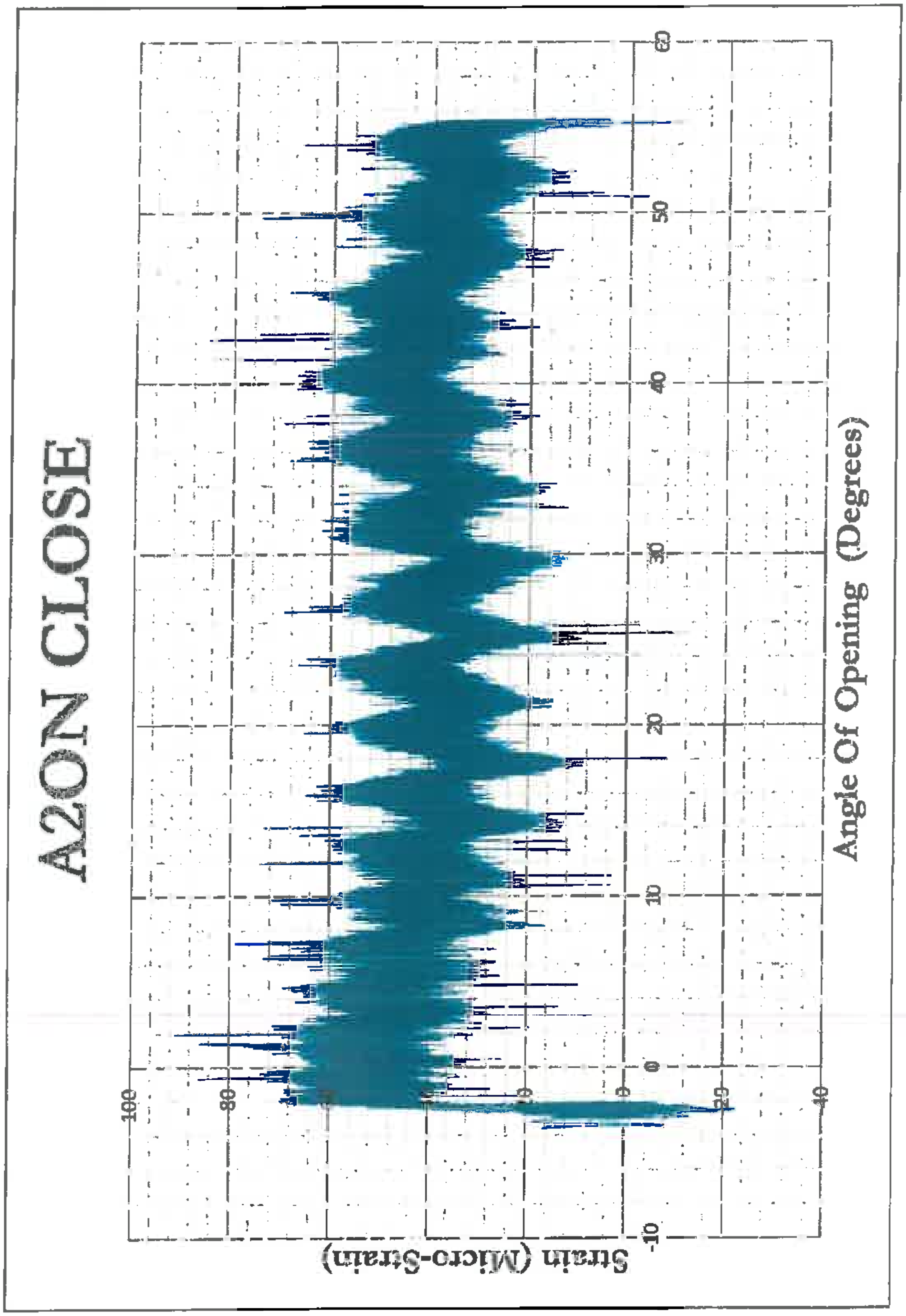



A2IS CLOSE
Strain (Micro-Strain)
100
90
80
70
60
50
40
30
20
10
0
-10
0
10
20
30
40
50
60
Angle Of Opening (Degrees)

BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3

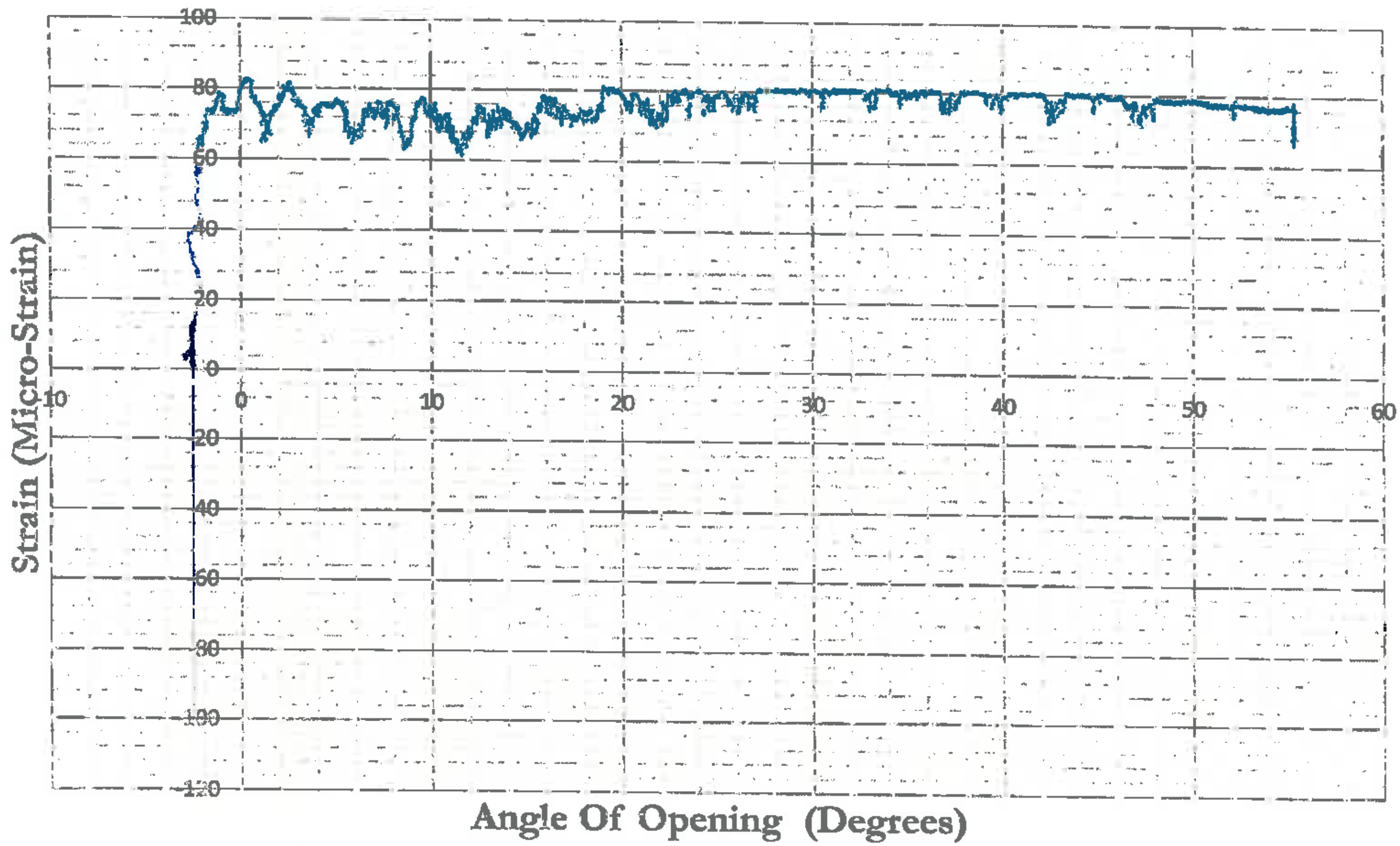


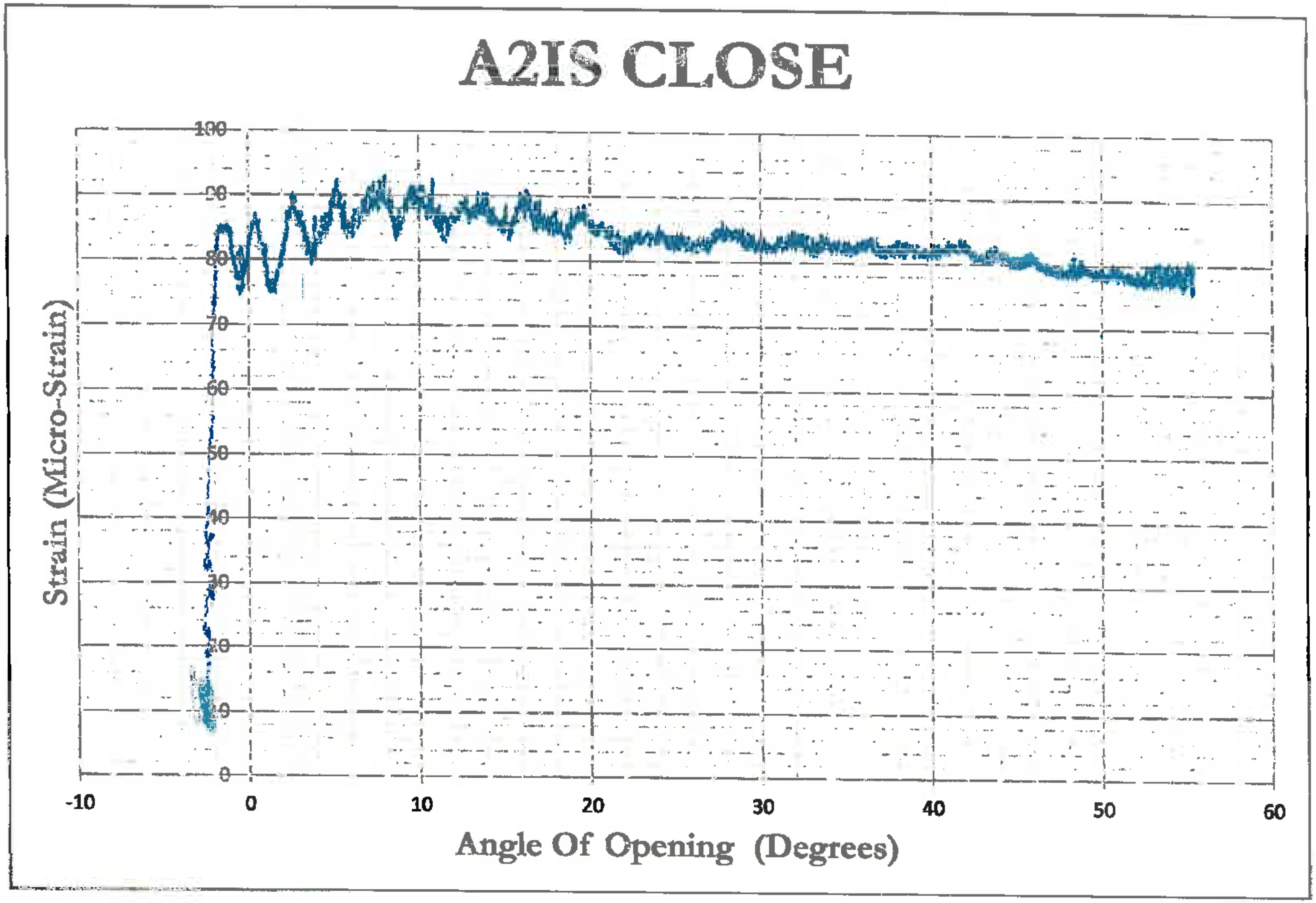
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



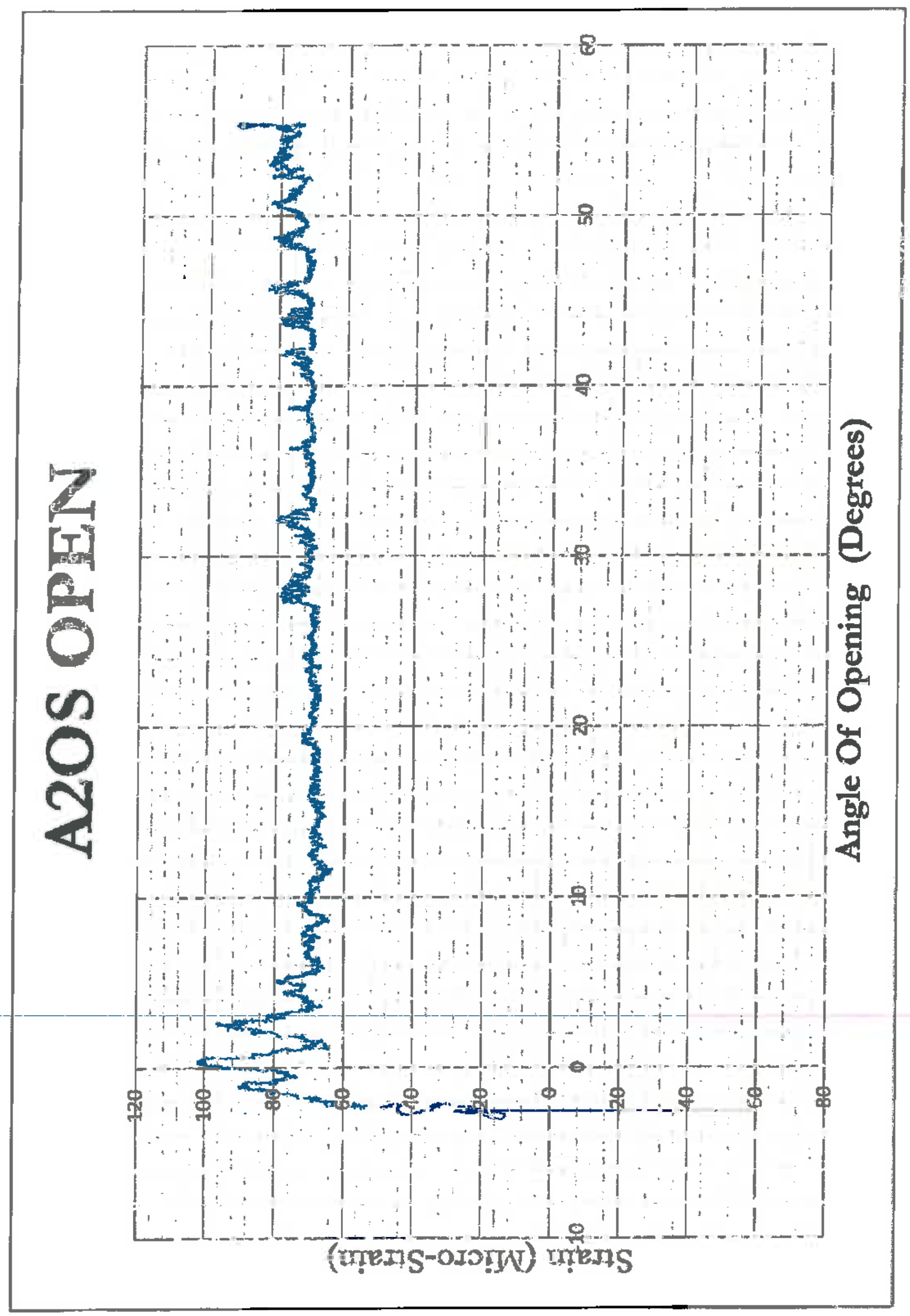
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3

A2IS OPEN

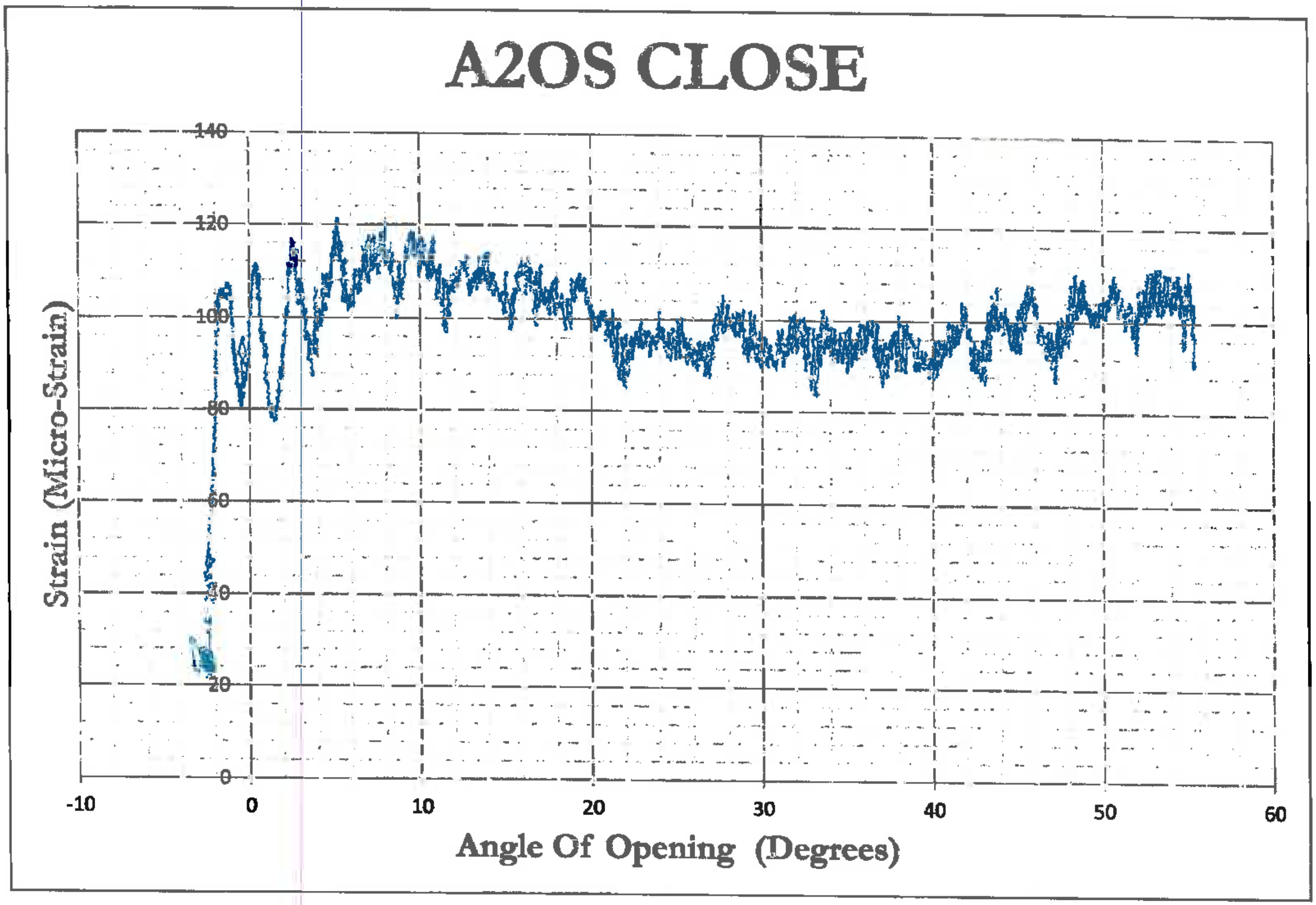



A2IS CLOSE
Strain (Micro-Strain)
100
90
80
70
60
50
40
30
20
10
0
-10
0
10
20
30
40
50
60
Angle Of Opening (Degrees)

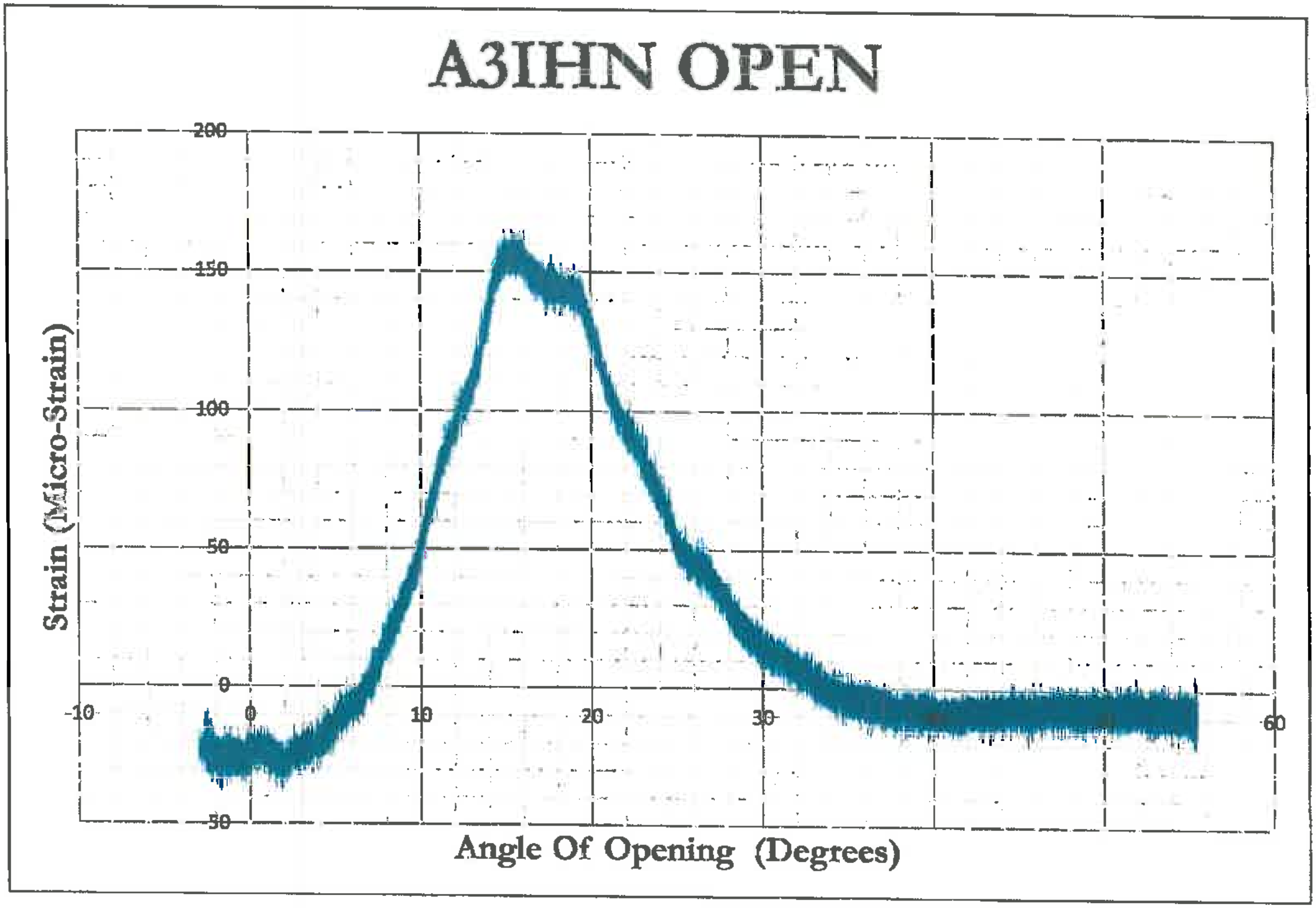
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



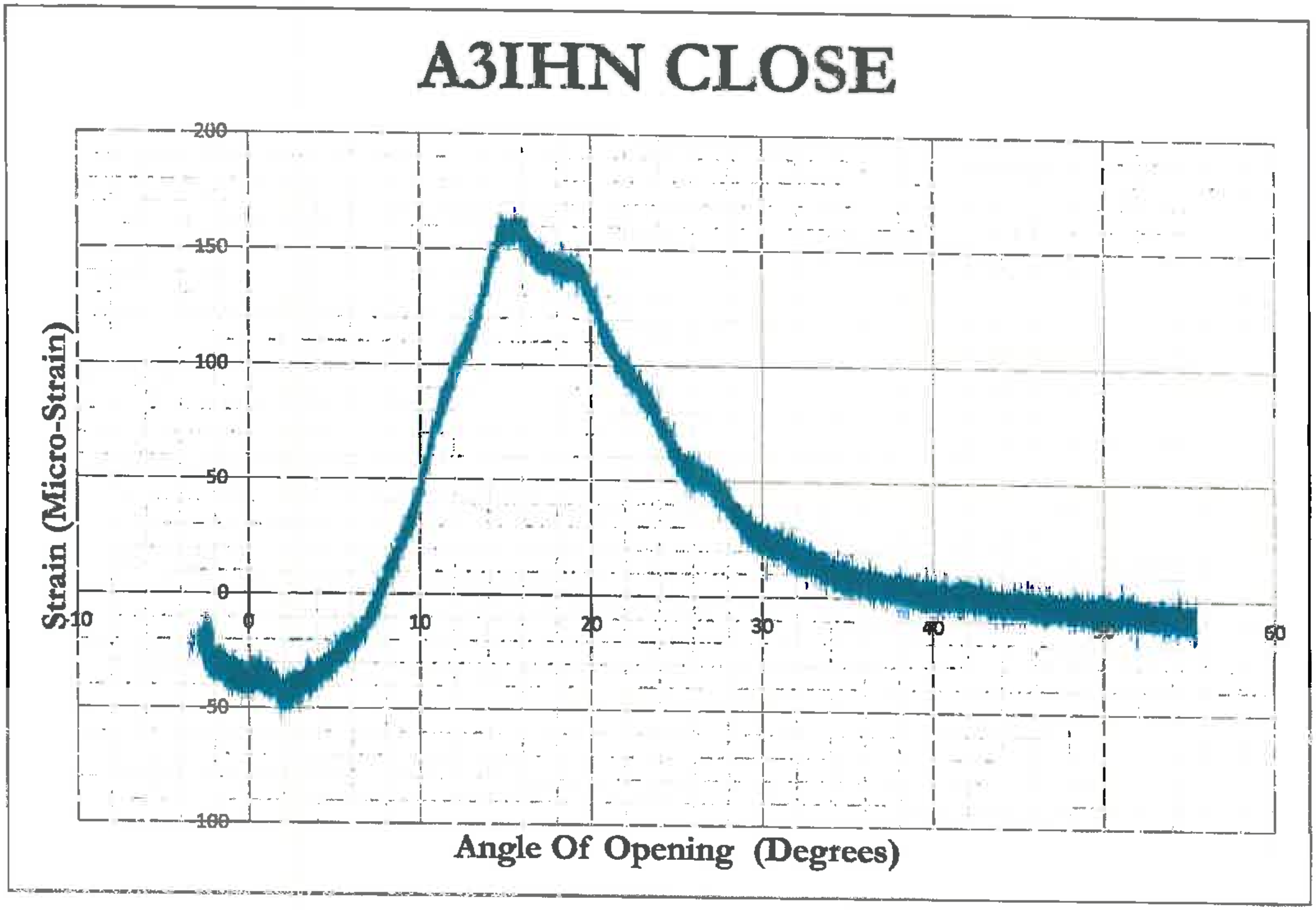
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3

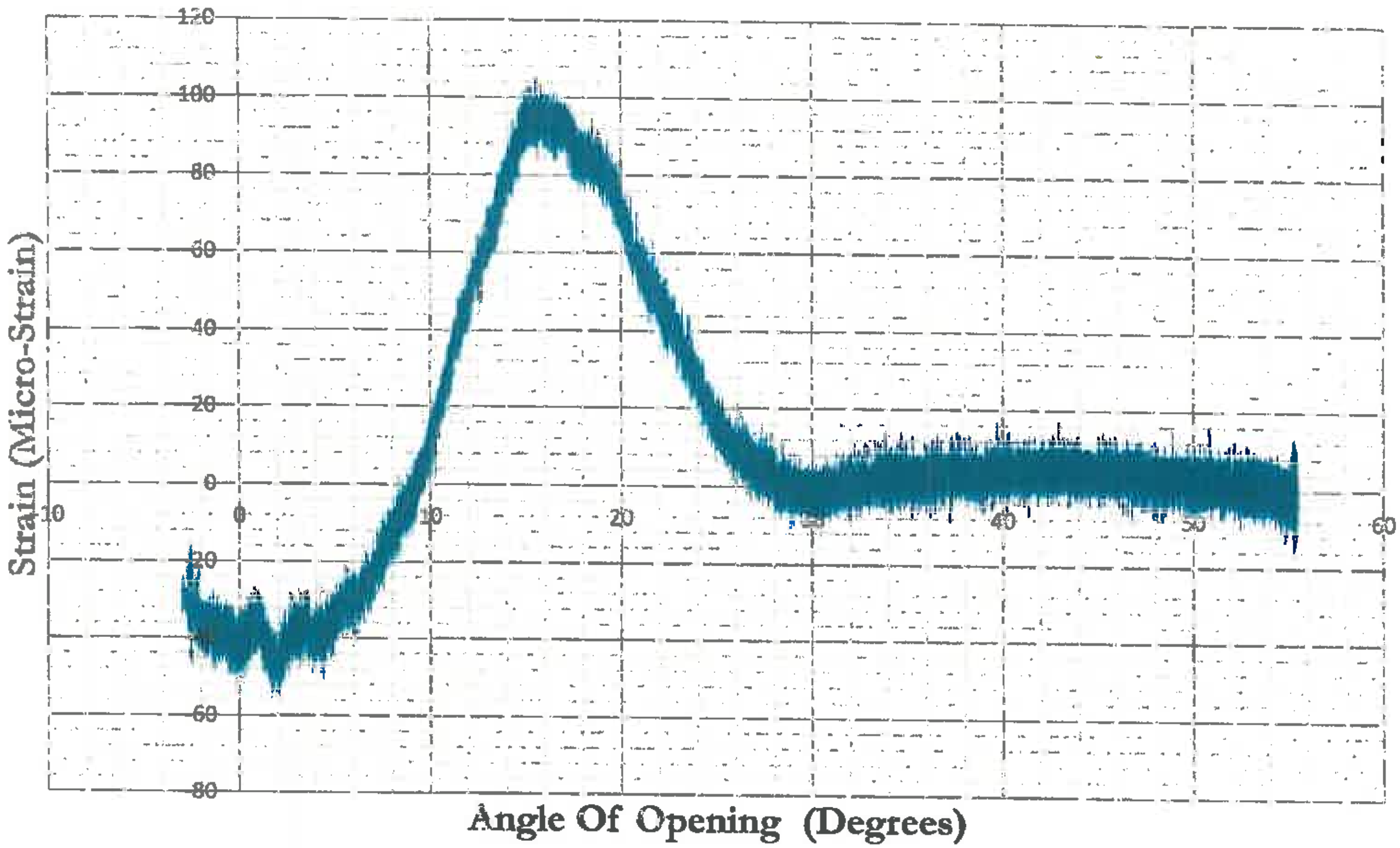


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3

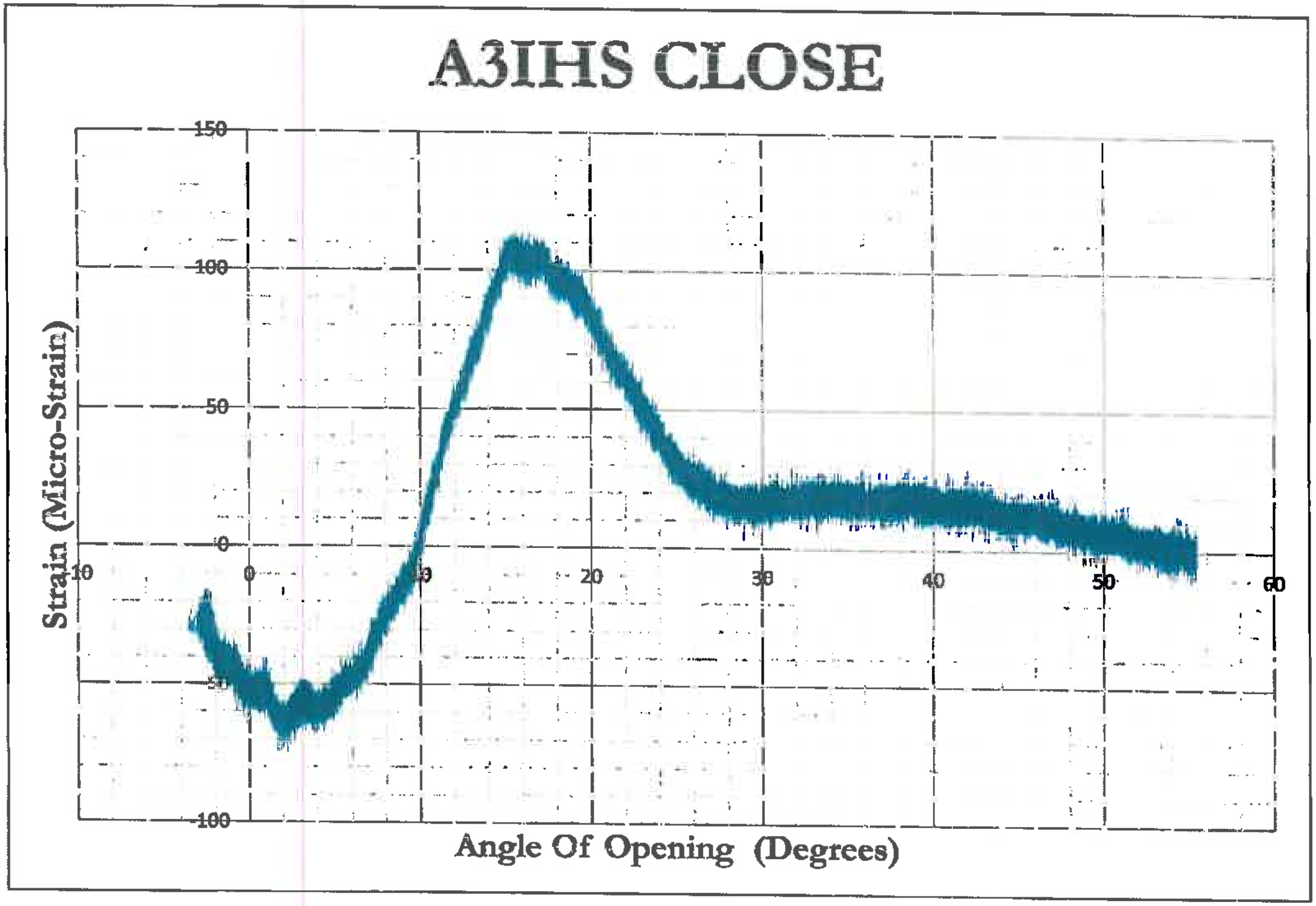


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3

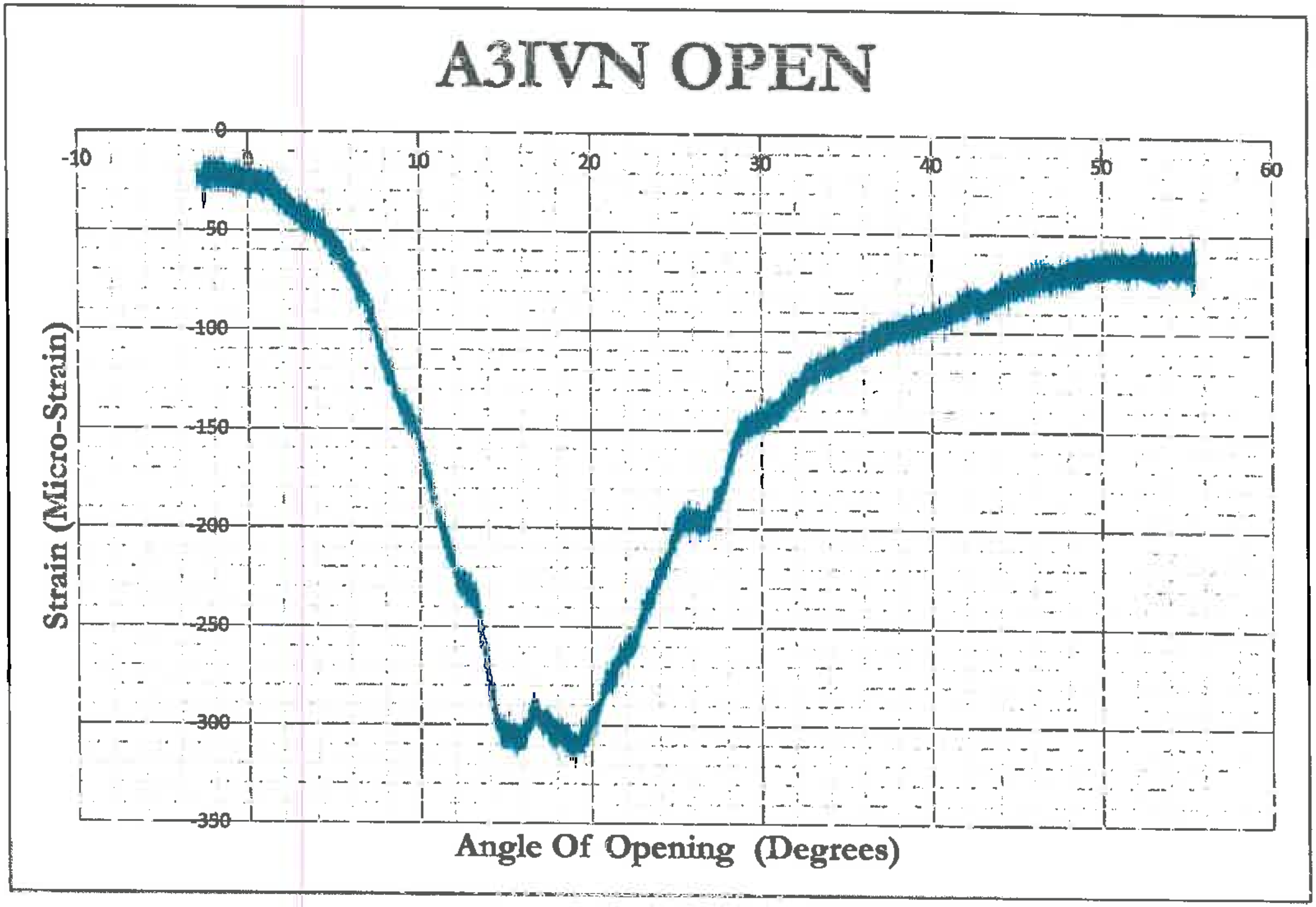
A3IHS OPEN



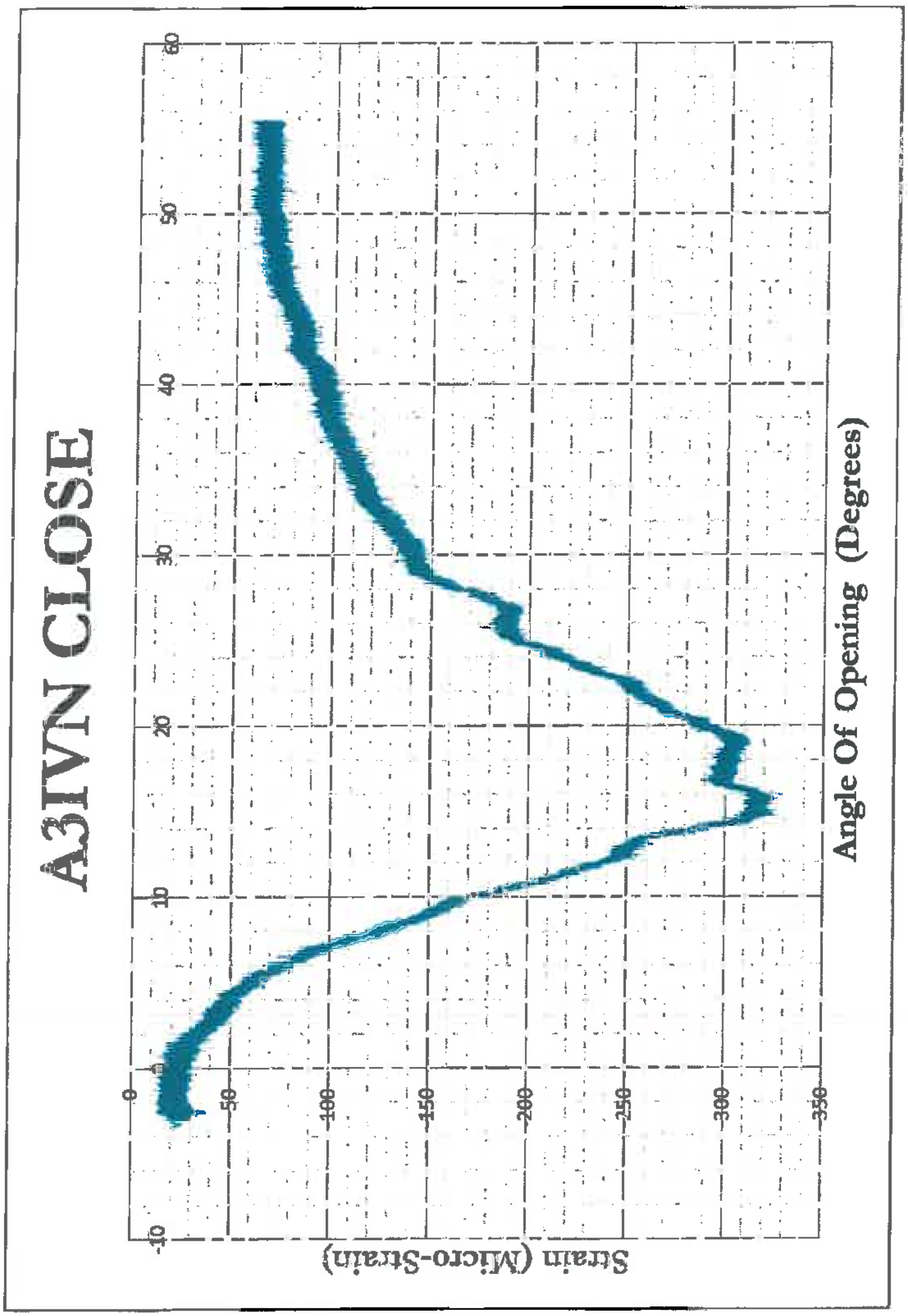
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



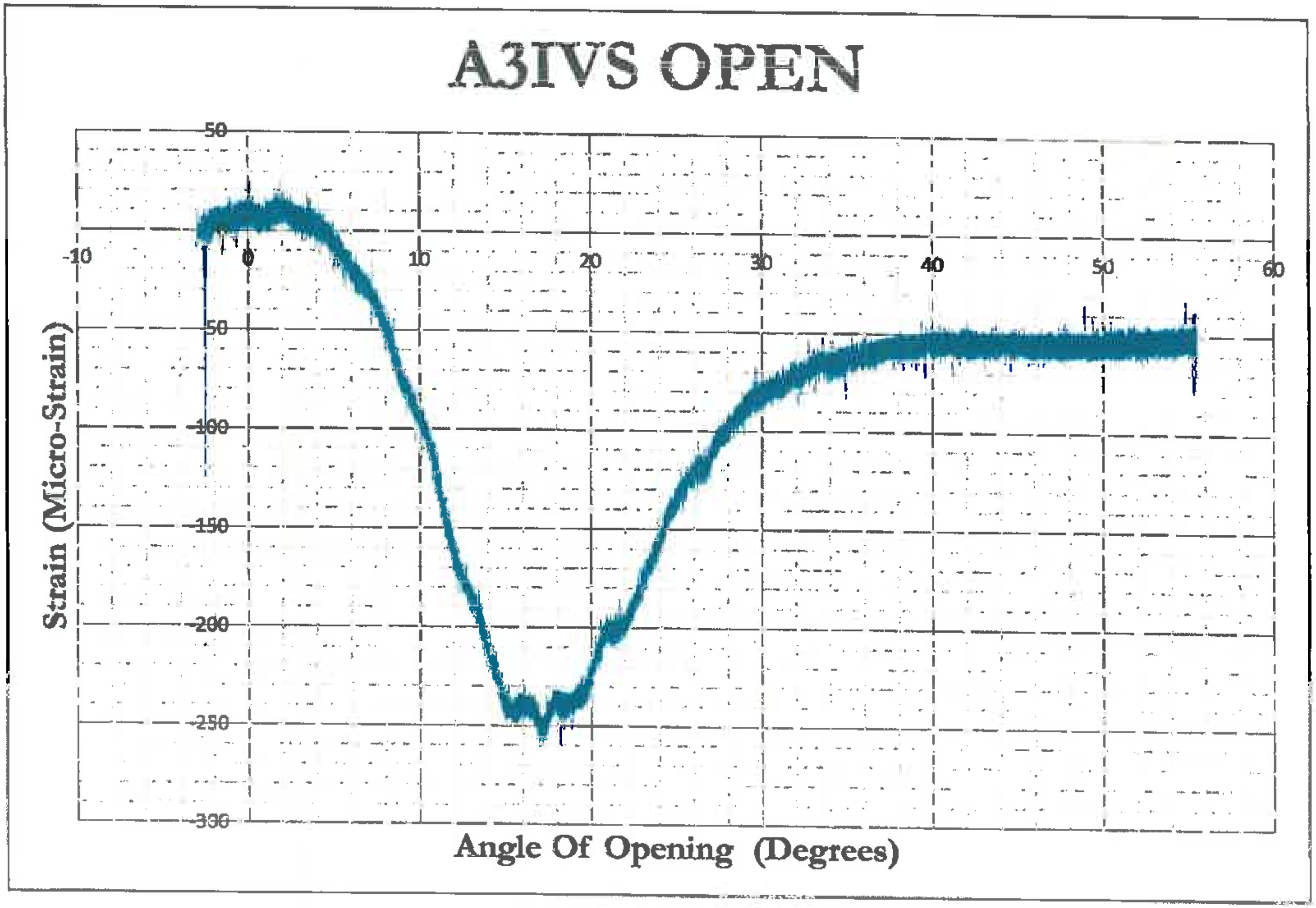
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



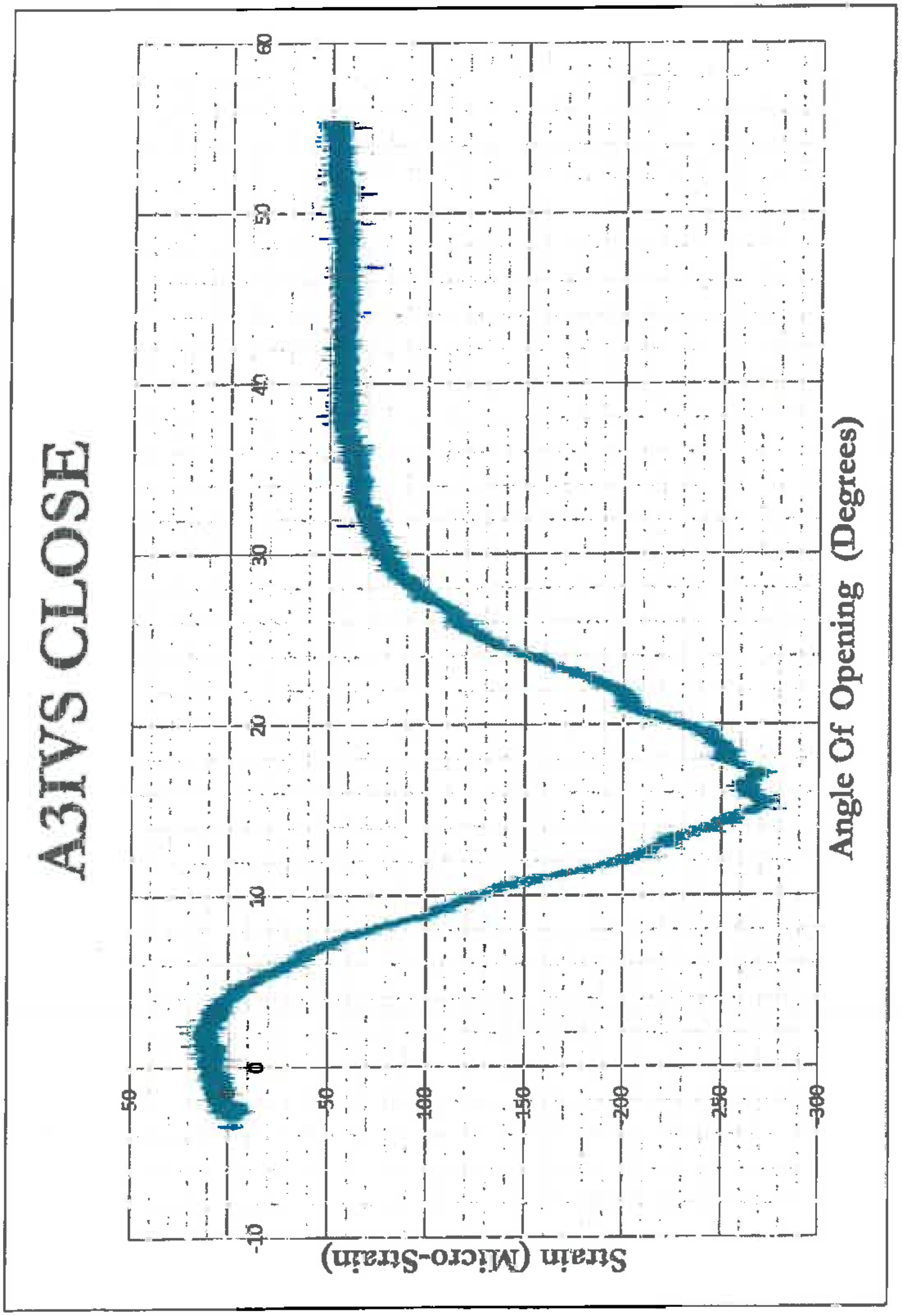
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



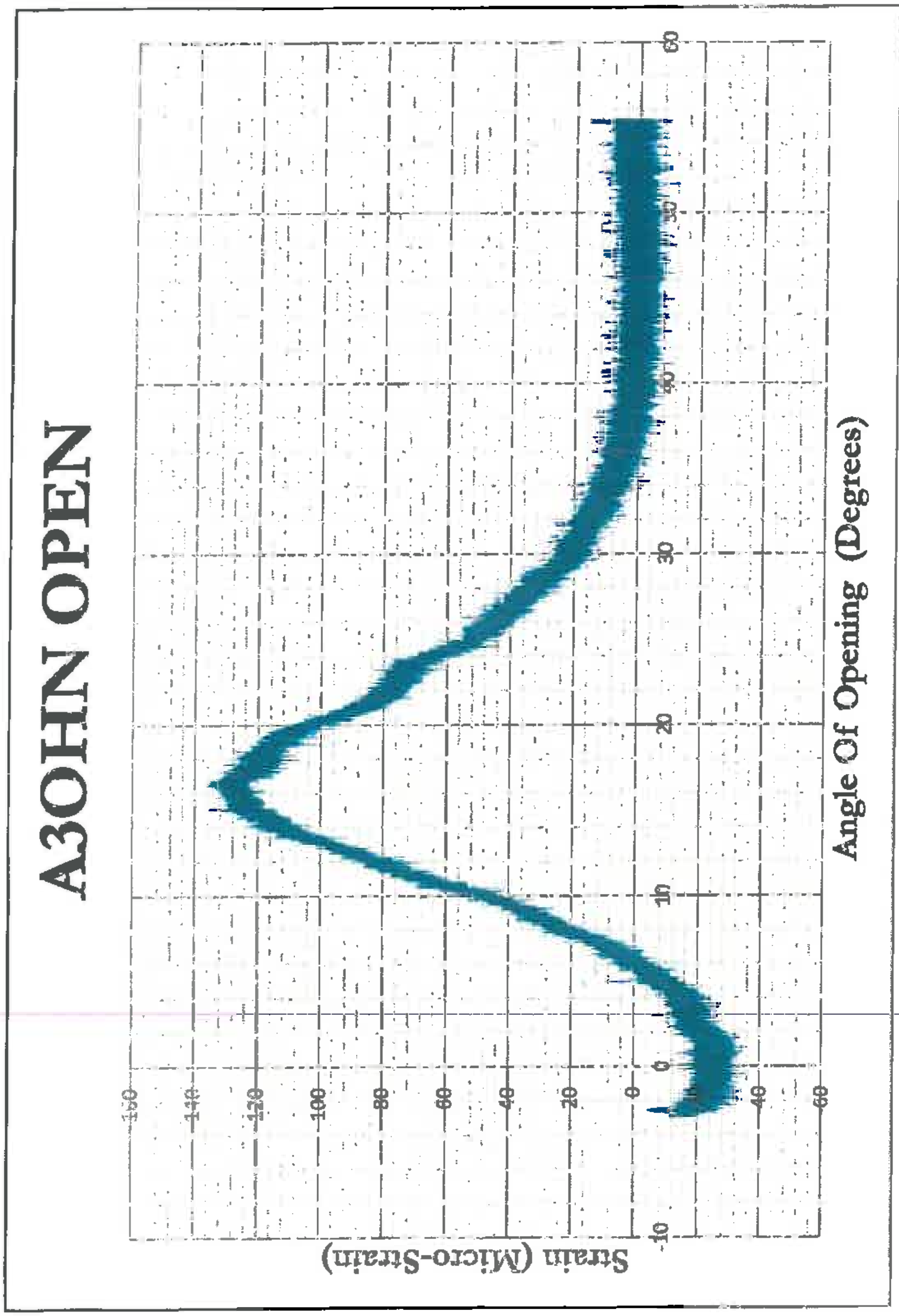
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



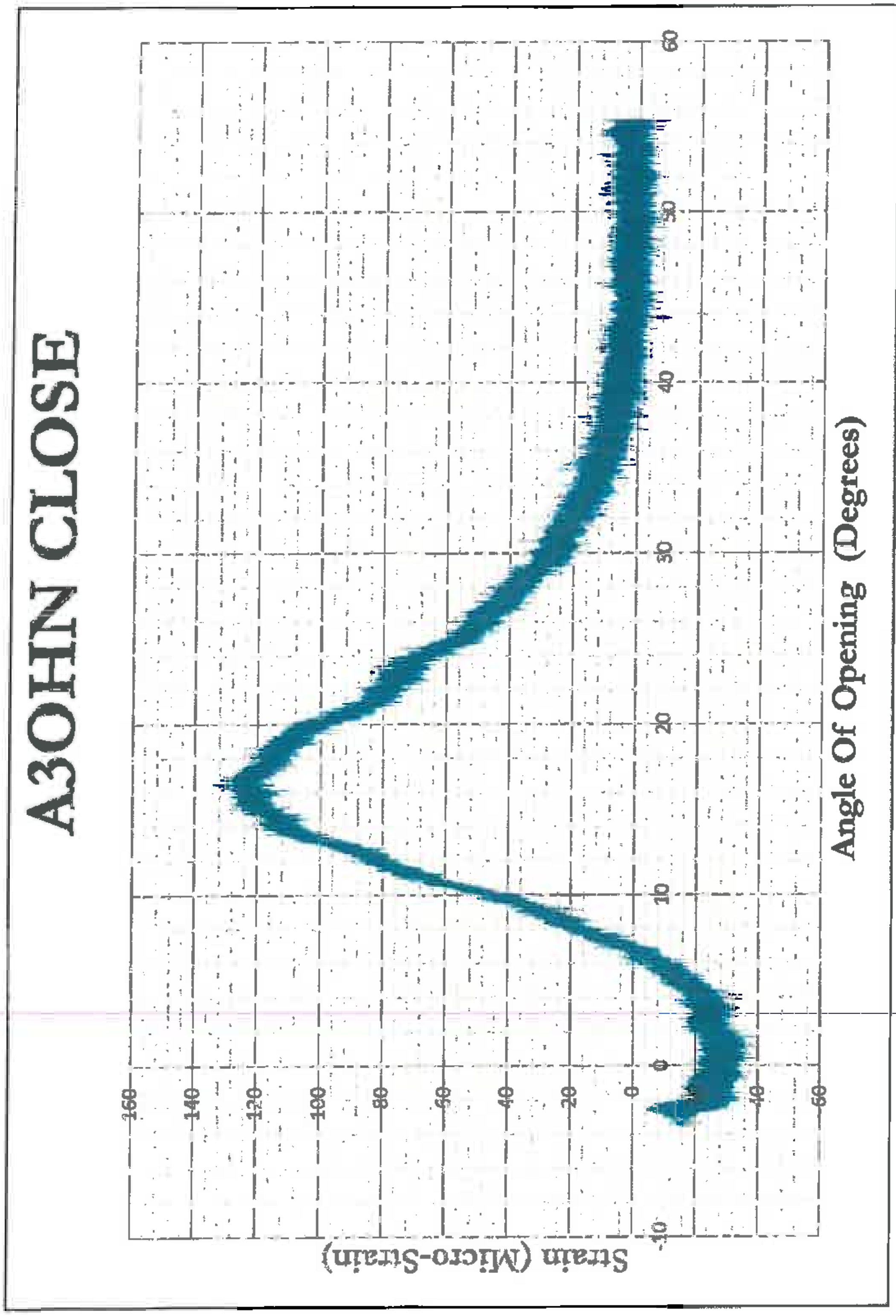
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



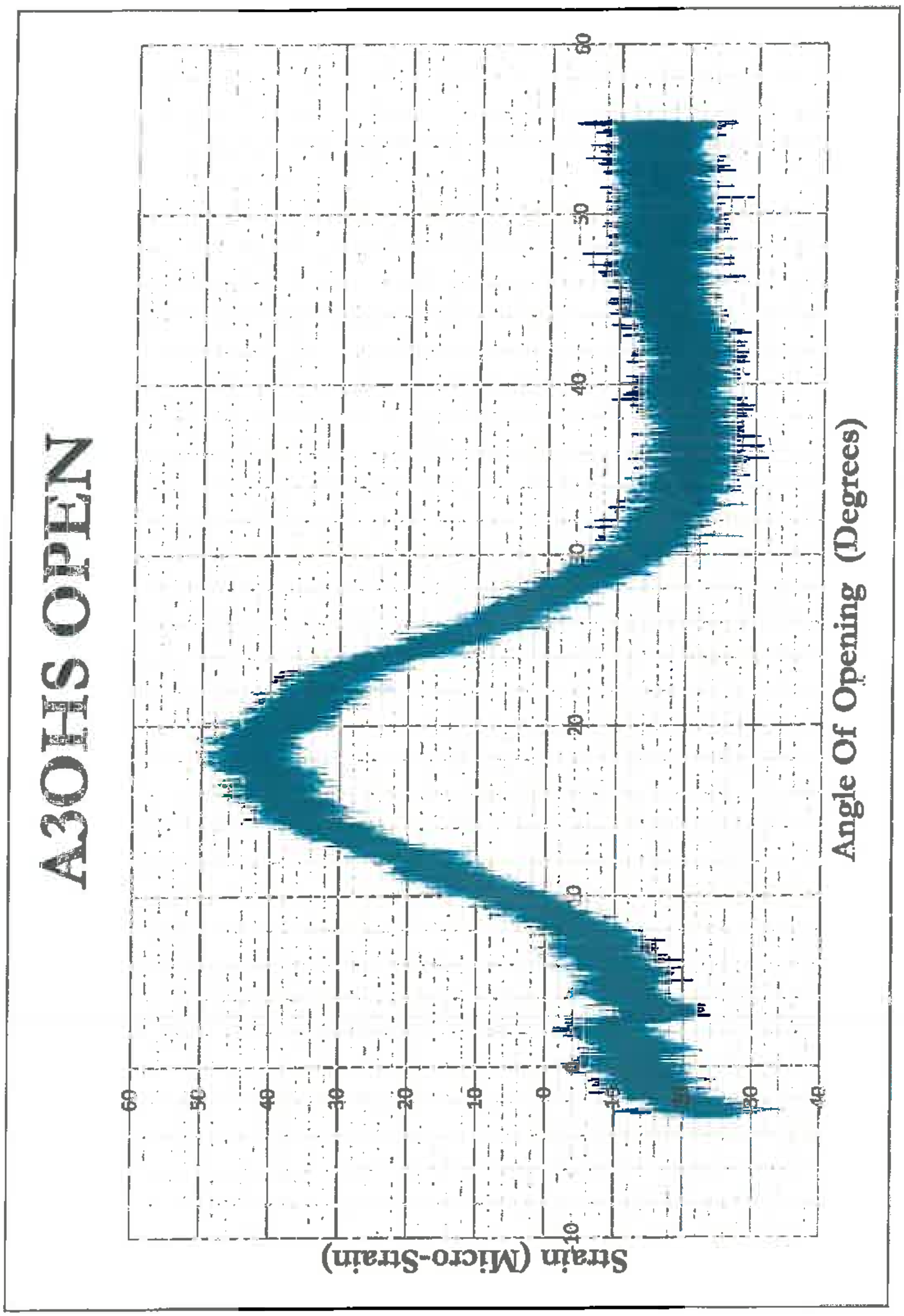
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



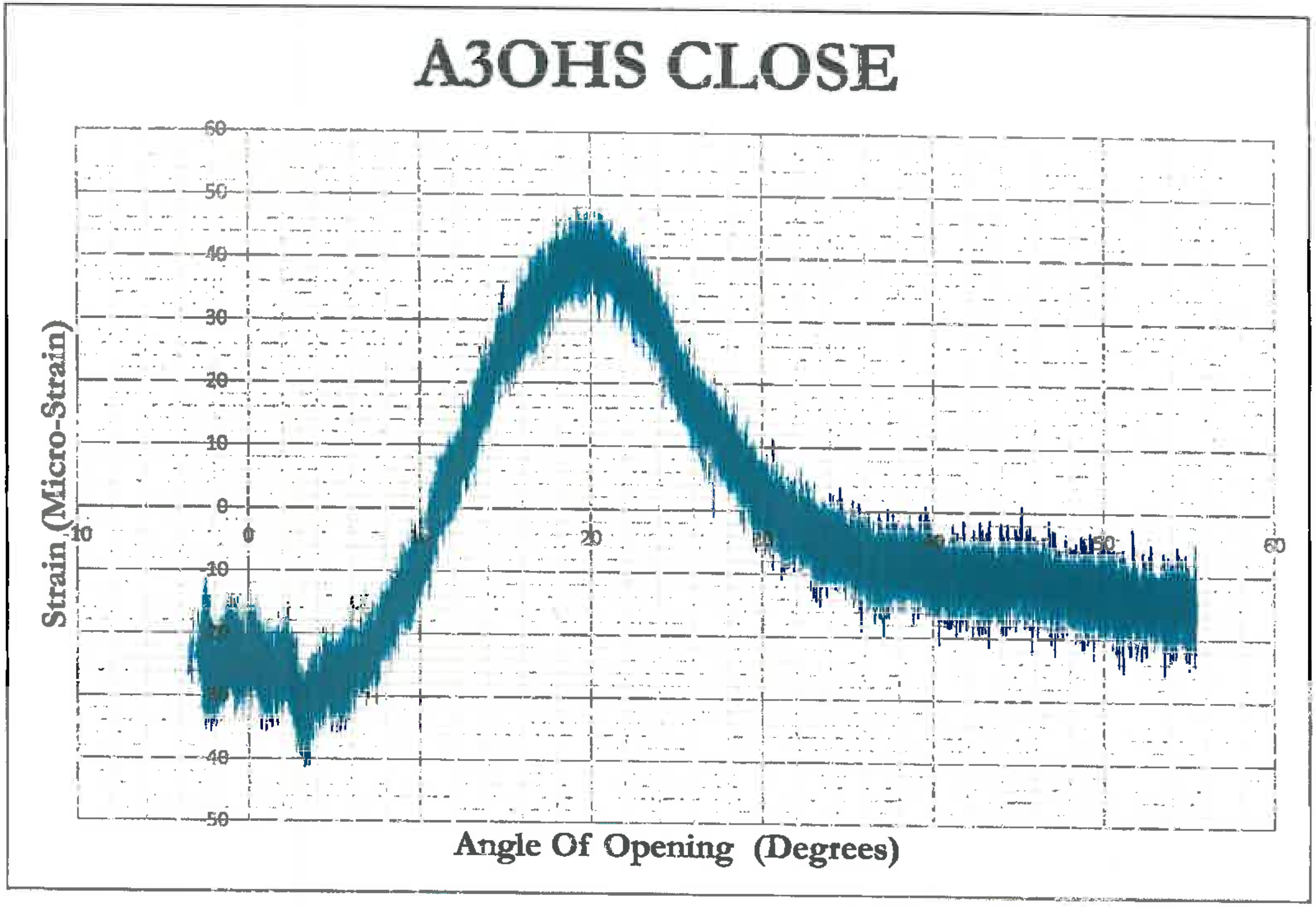
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



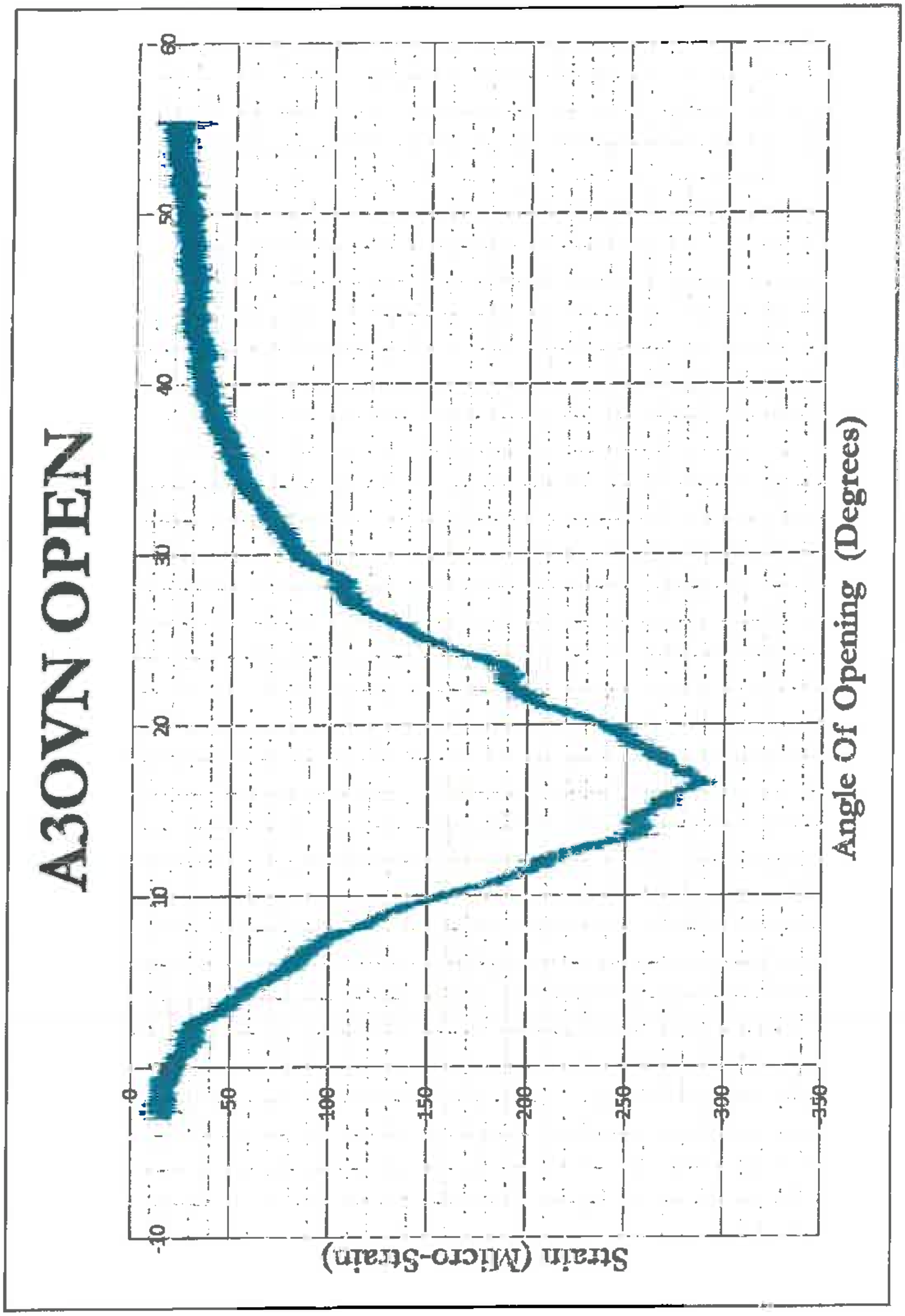
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



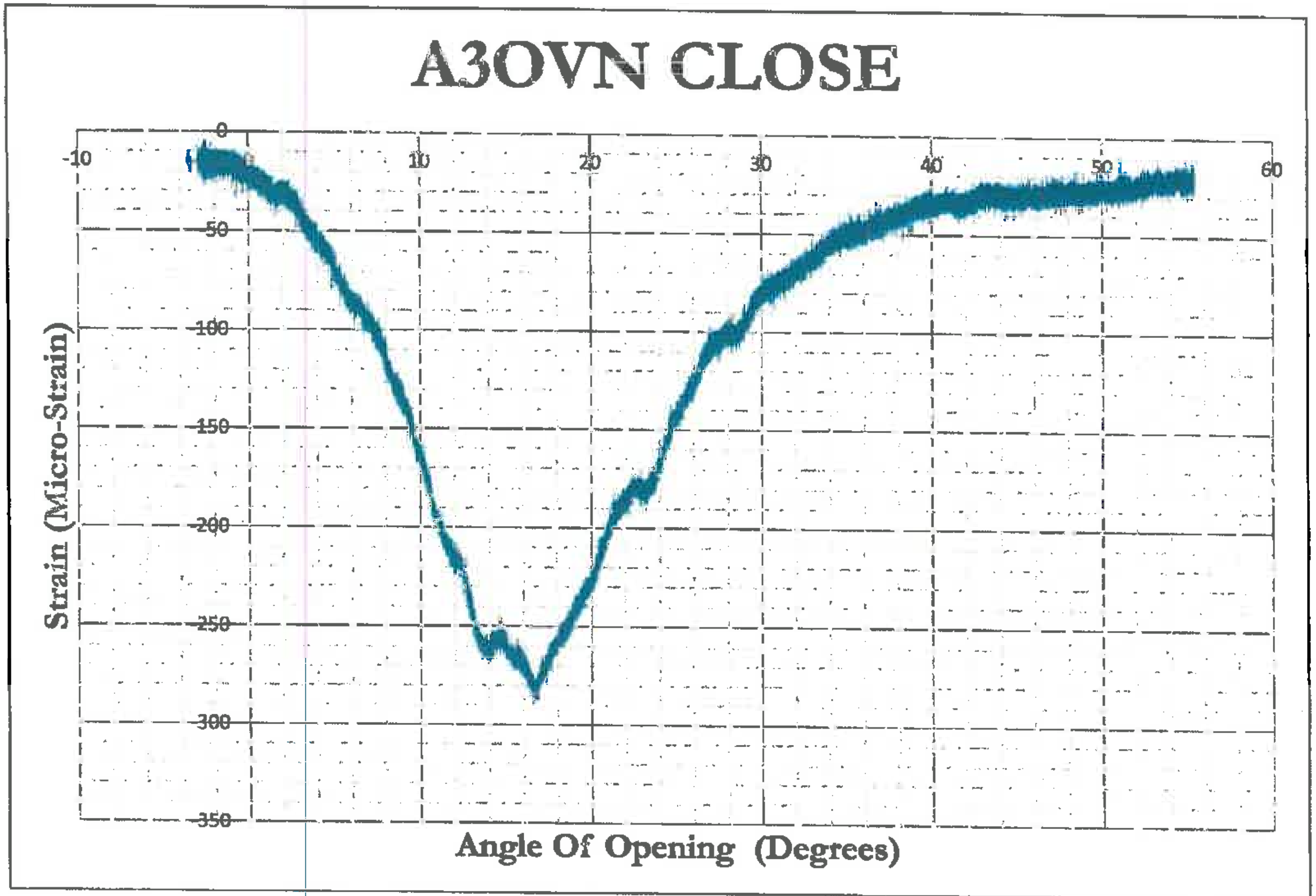
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



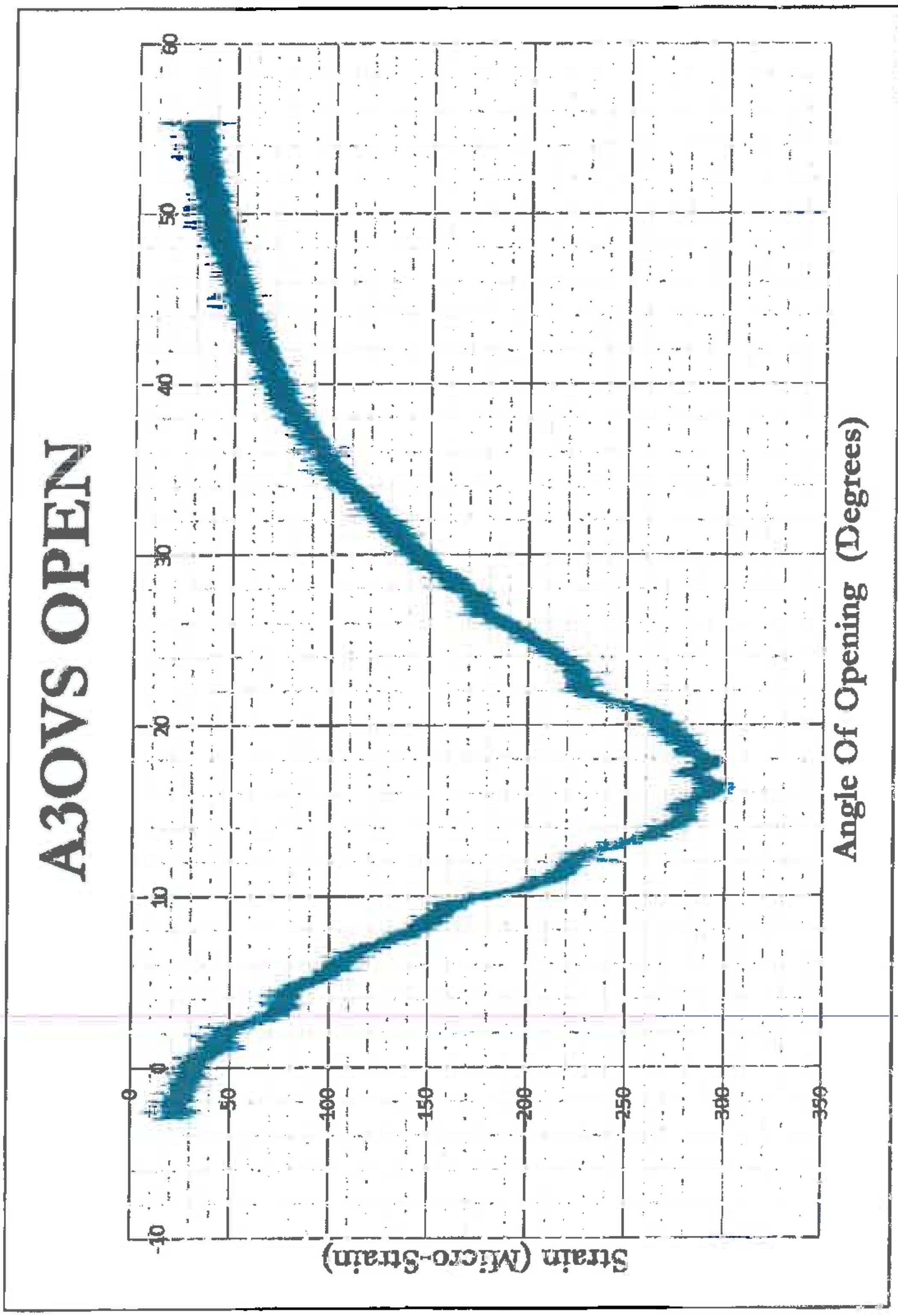
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



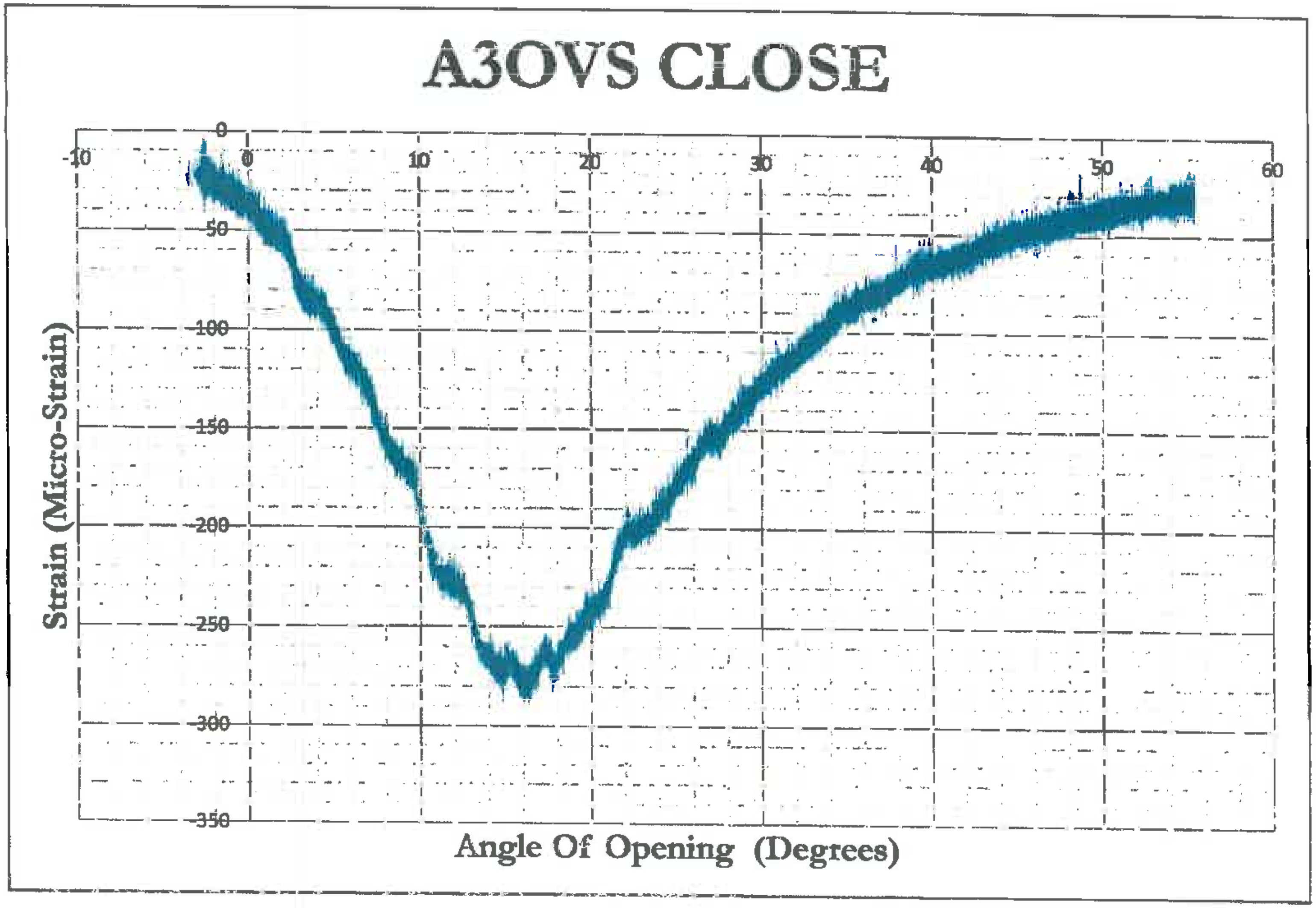
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



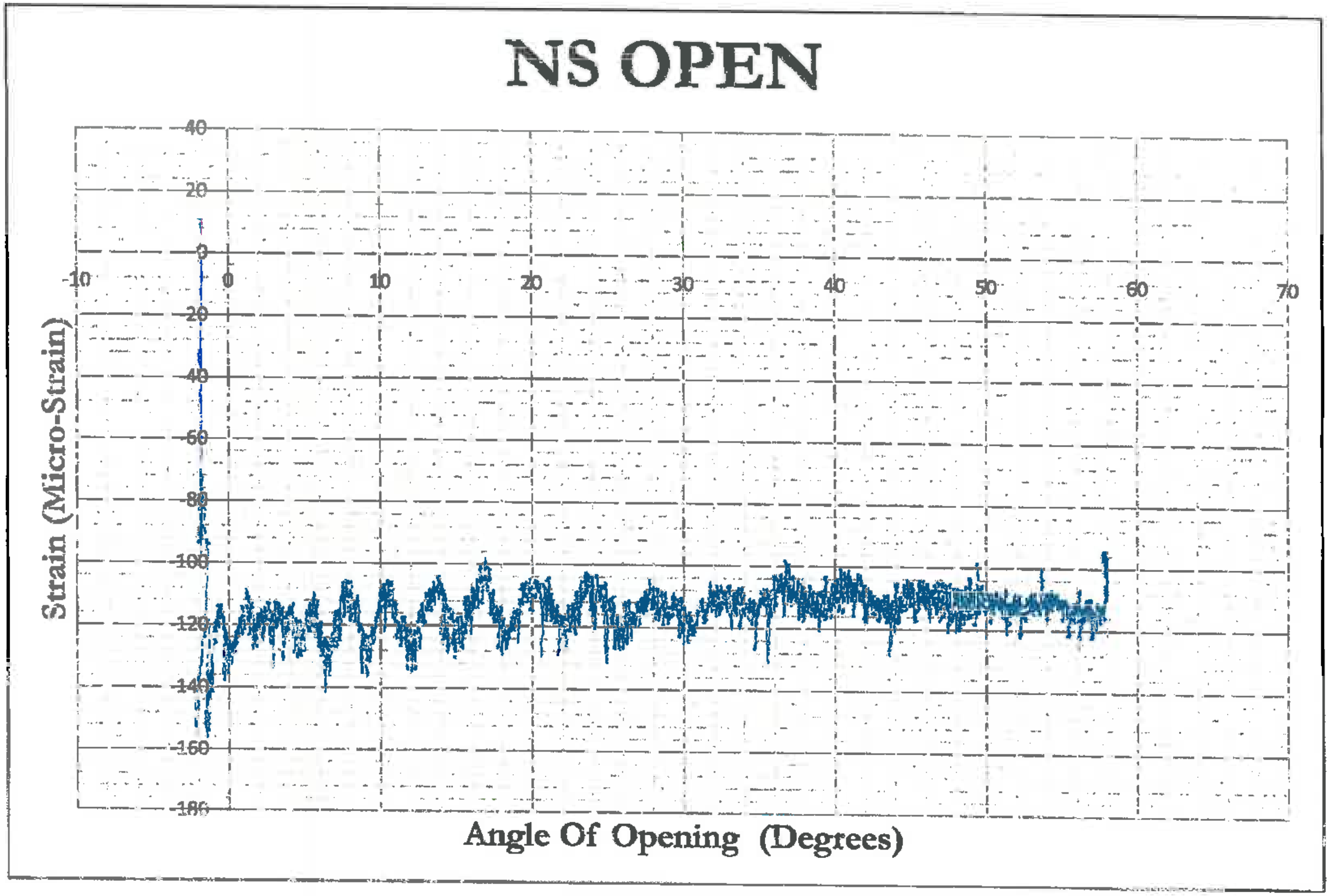
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
TEST #3



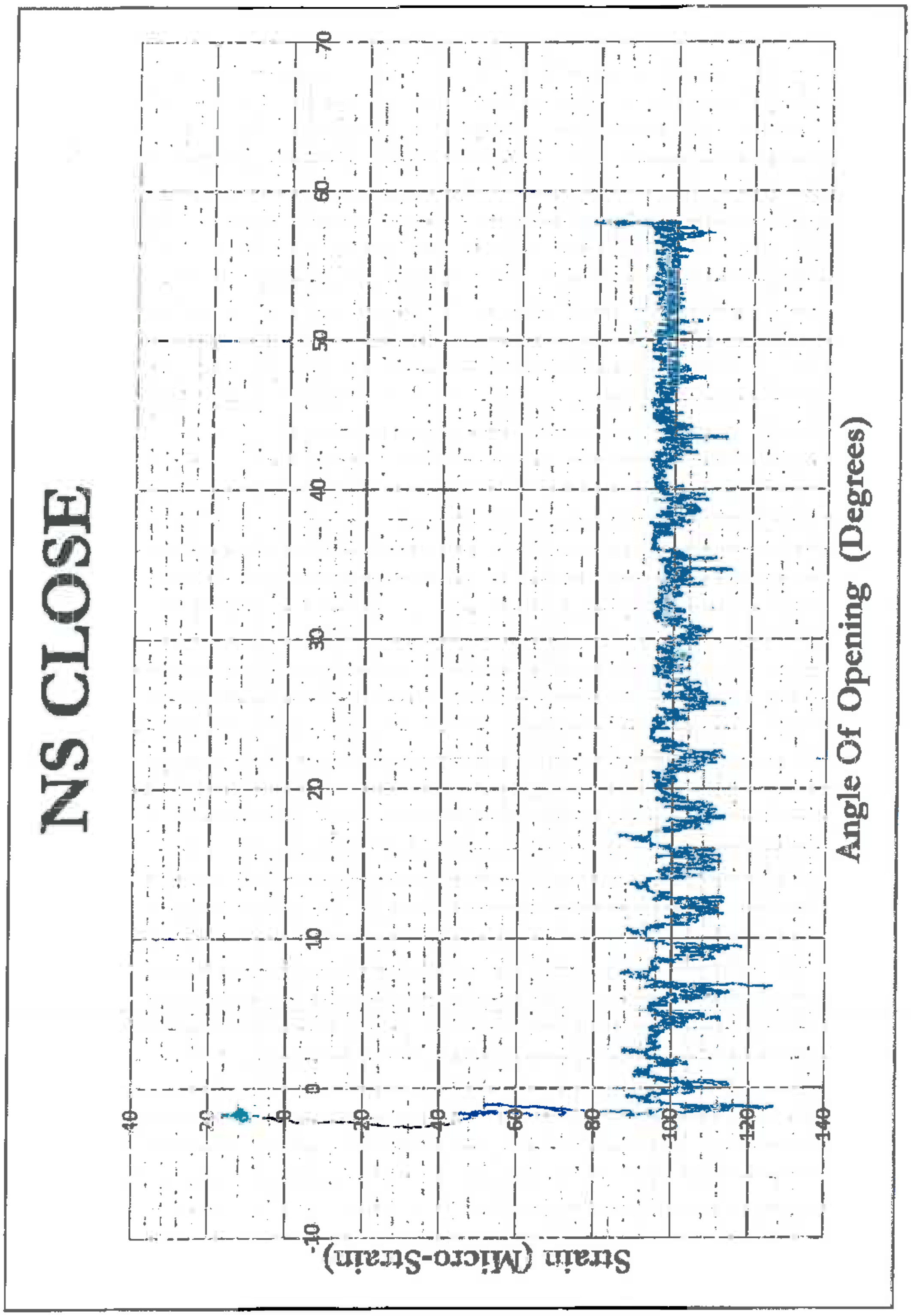
BROADWAY BRIDGE - 02720.03
EAST BRIDGE
TEST #3

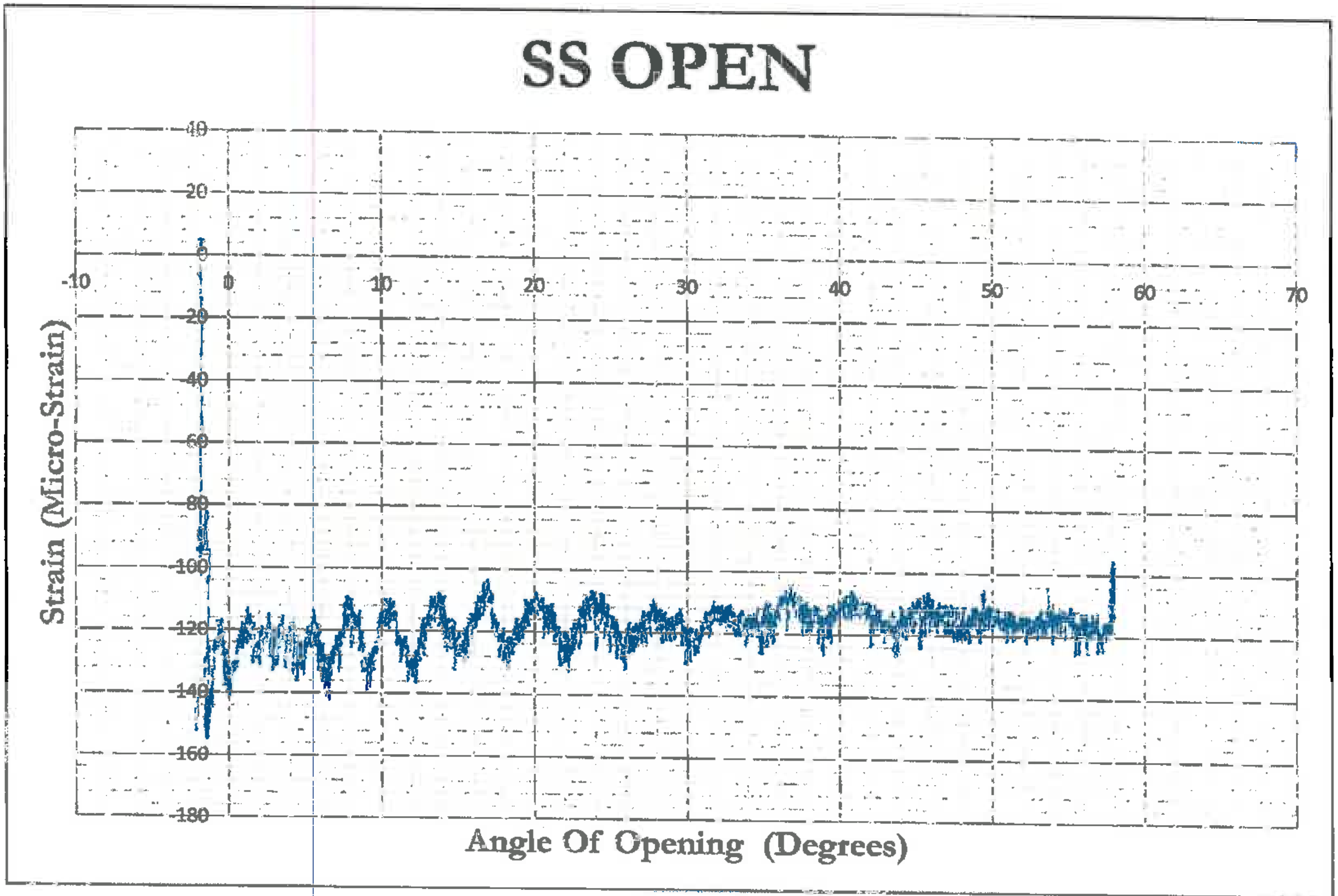


BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3

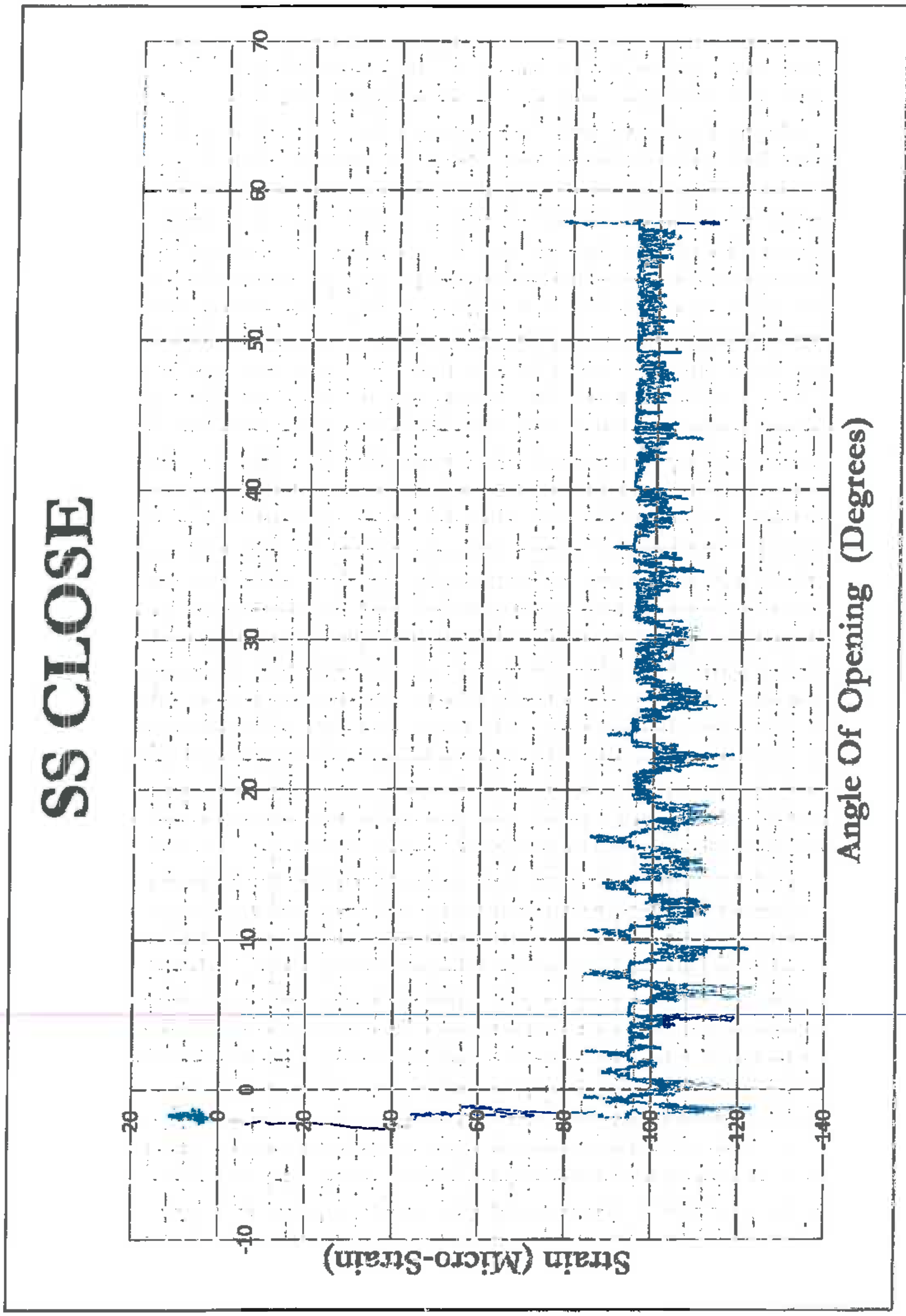


BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3

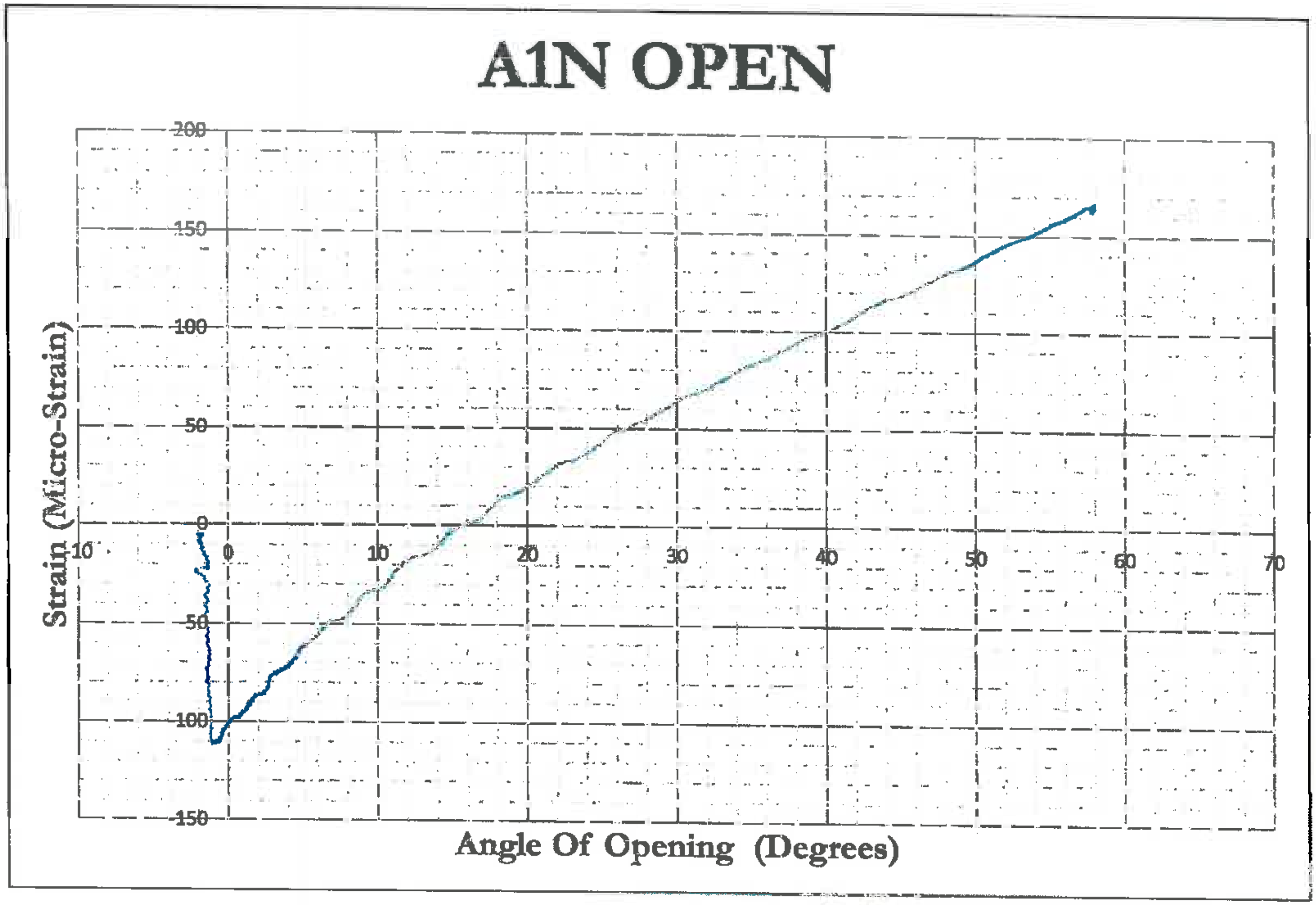



SS OPEN
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-10
0
10
20
30
40
50
60
70
Strain (Micro-Strain)
Angle Of Opening (Degrees)

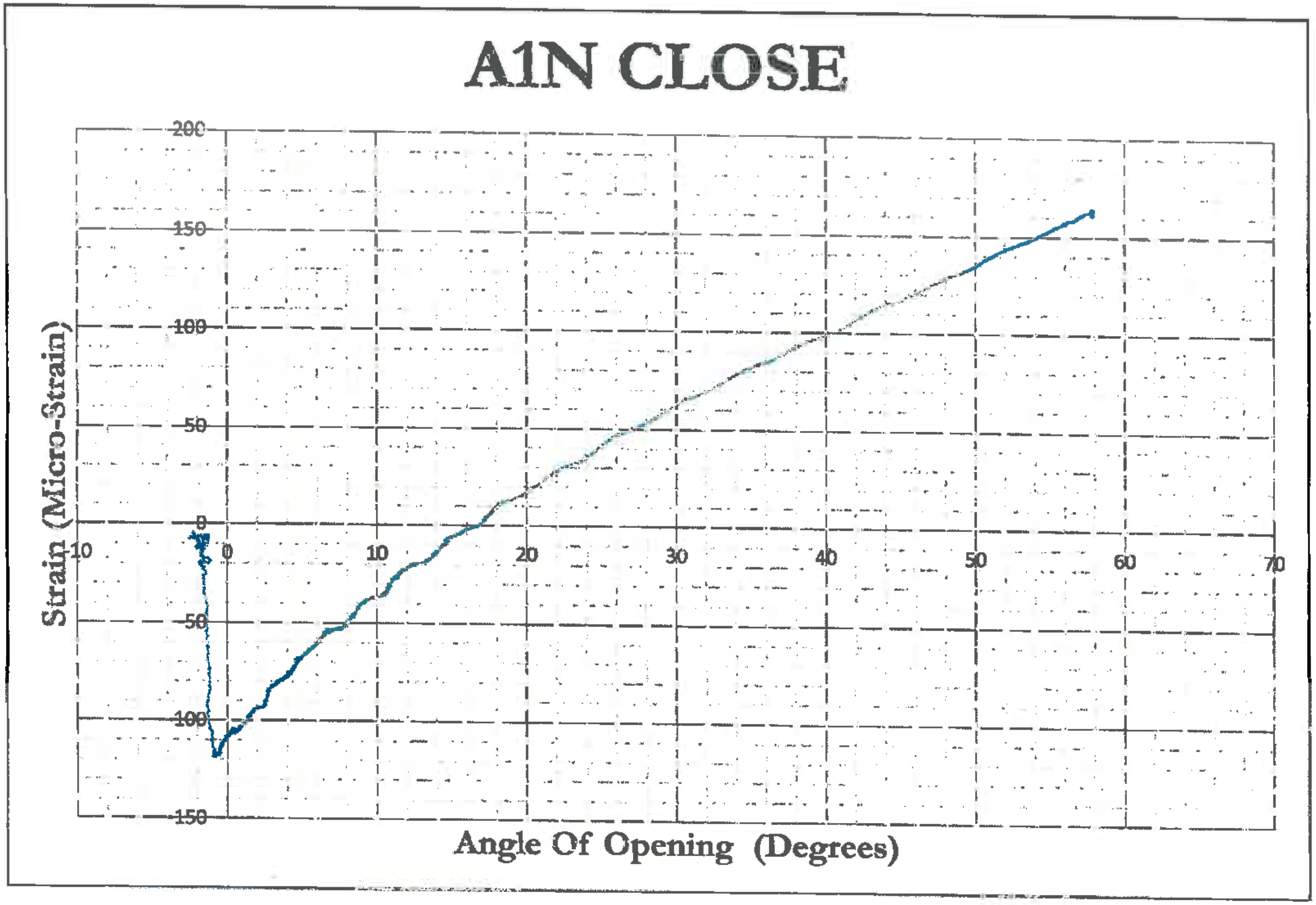
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



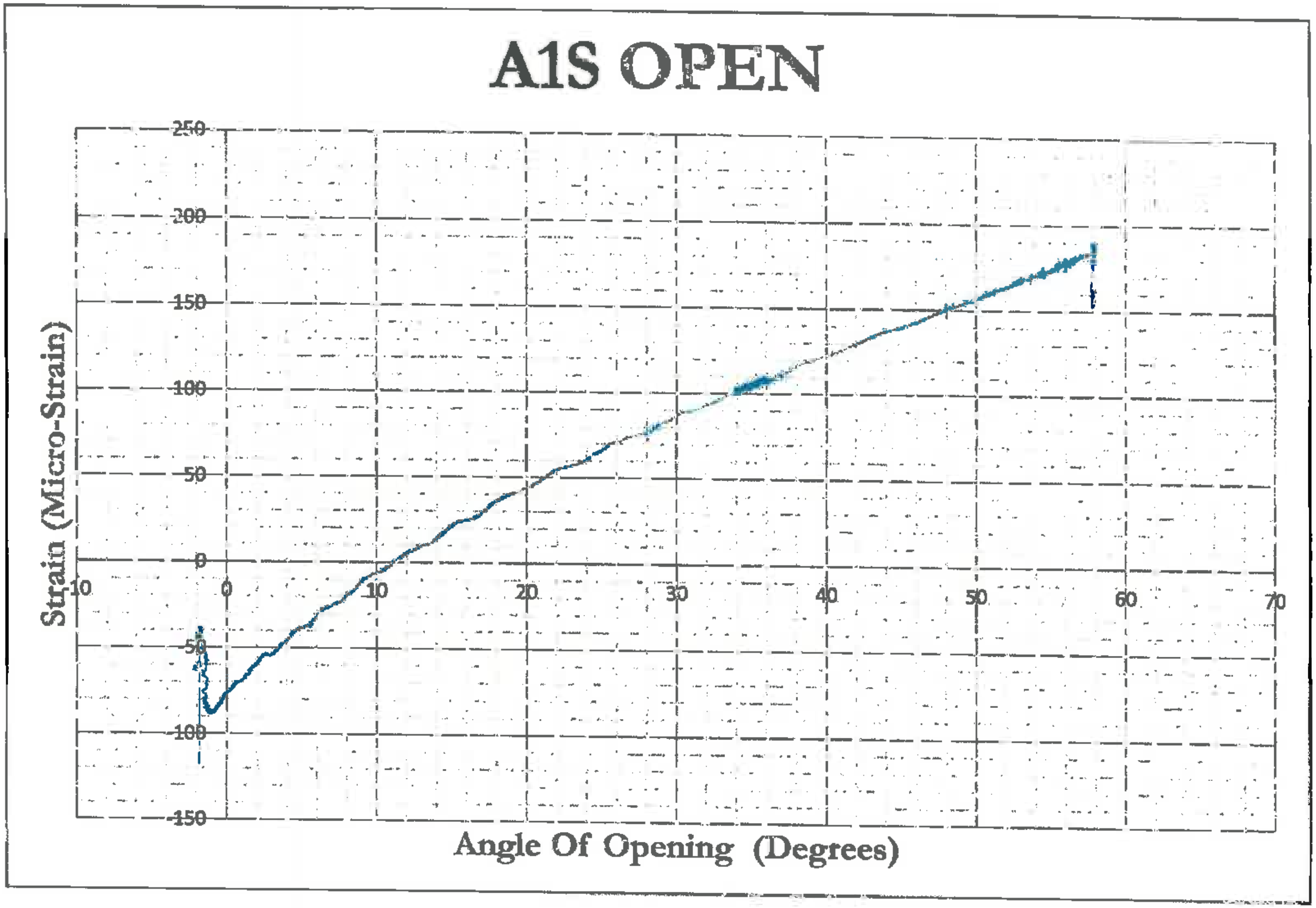
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



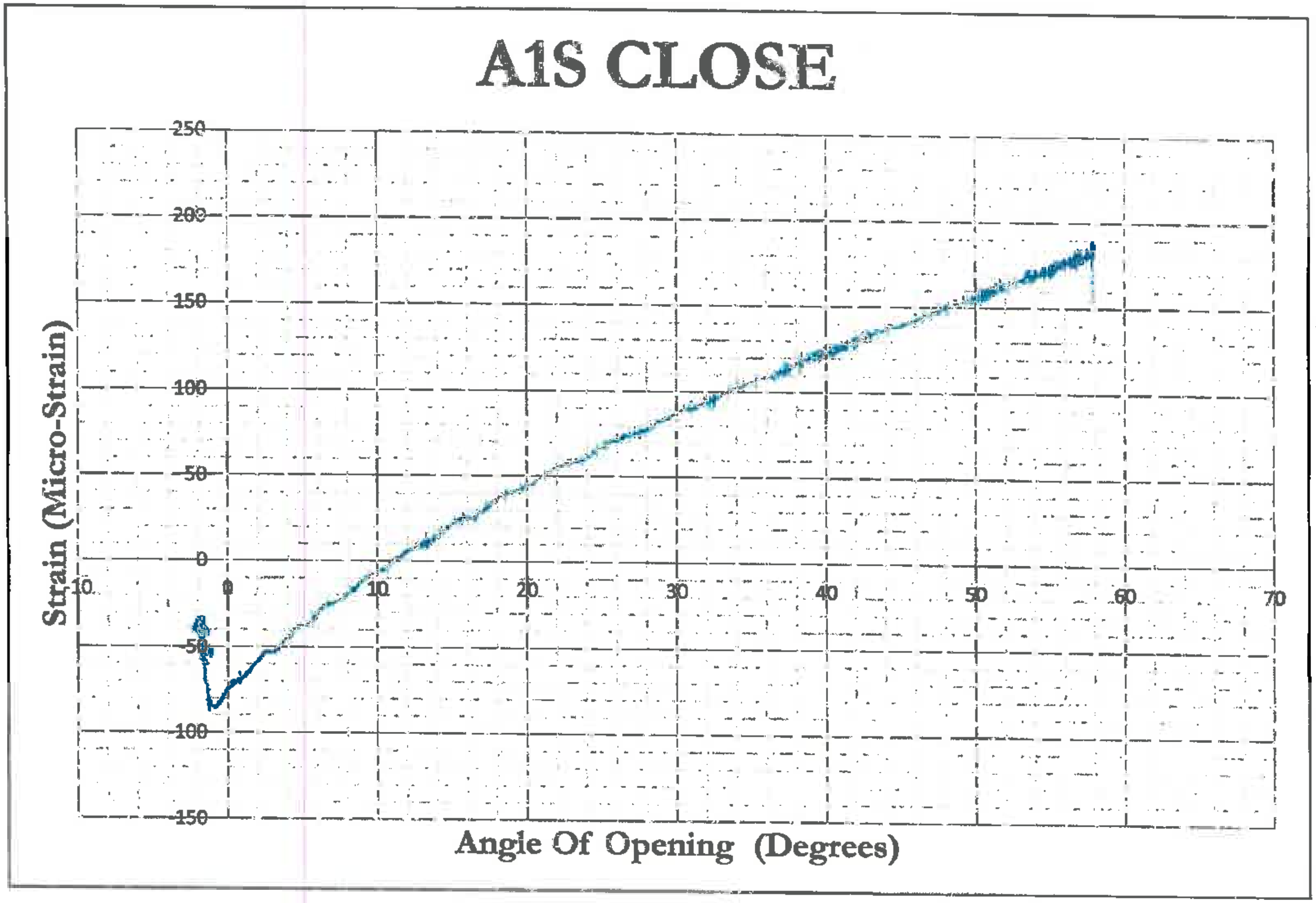
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



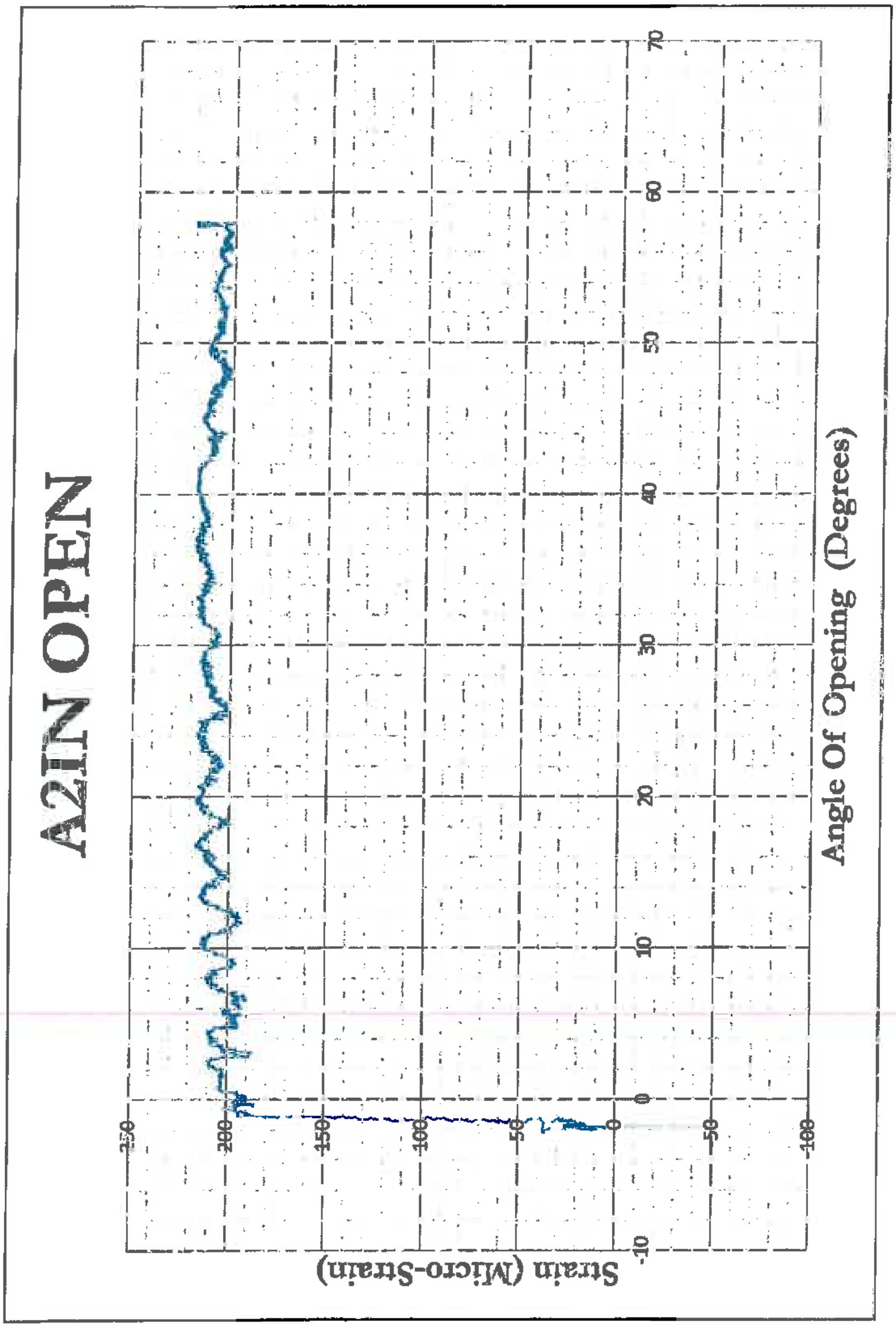
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



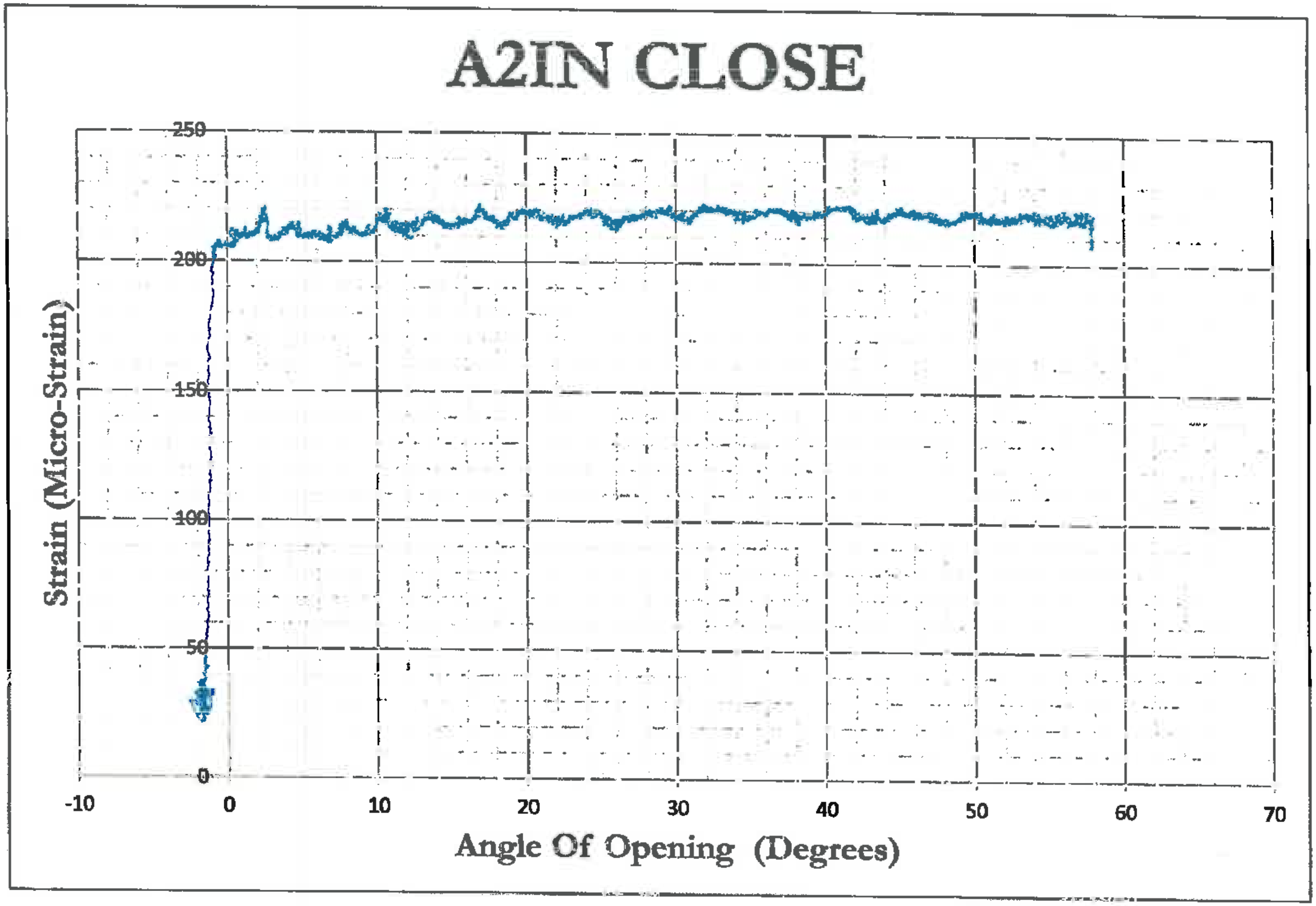
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



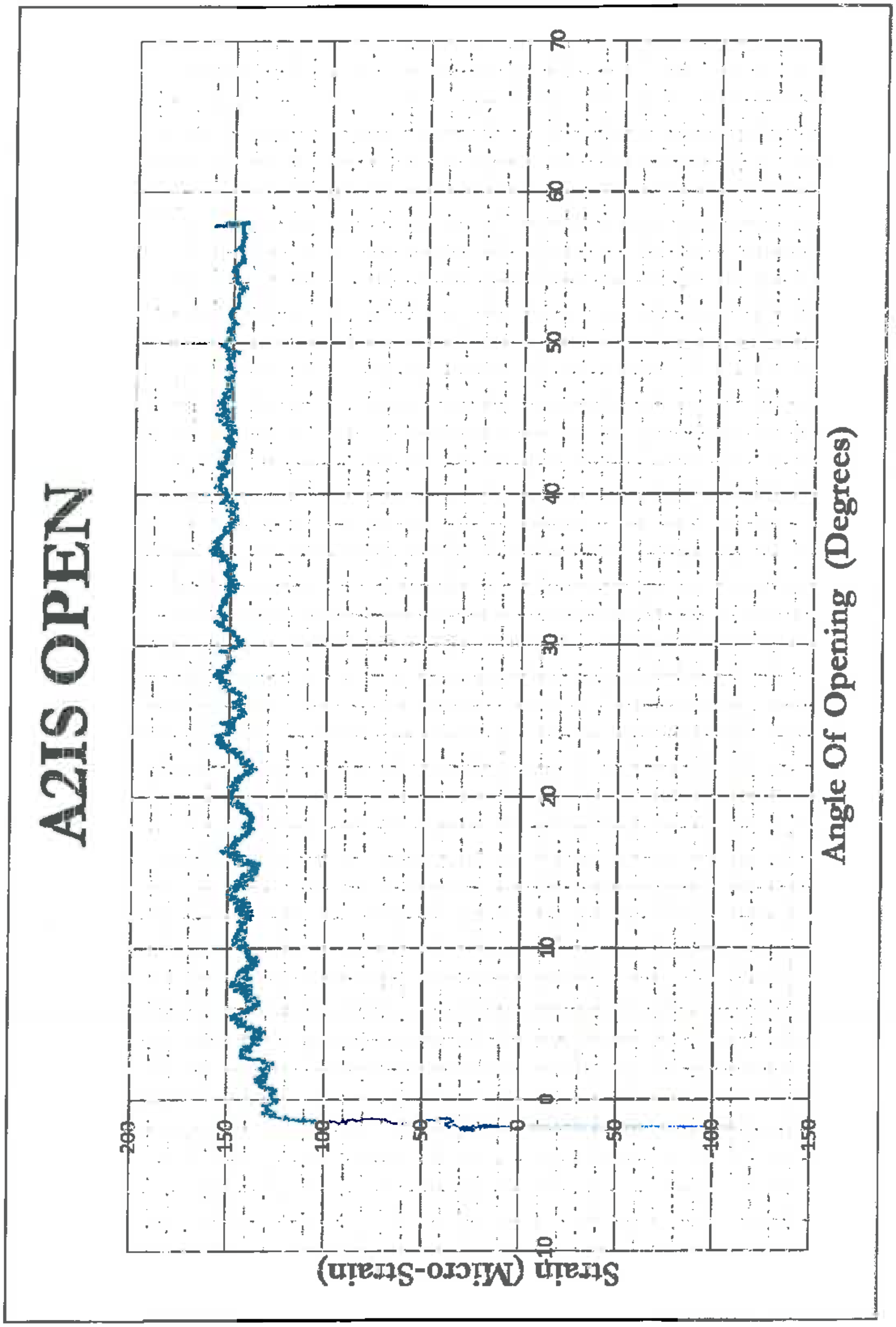
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



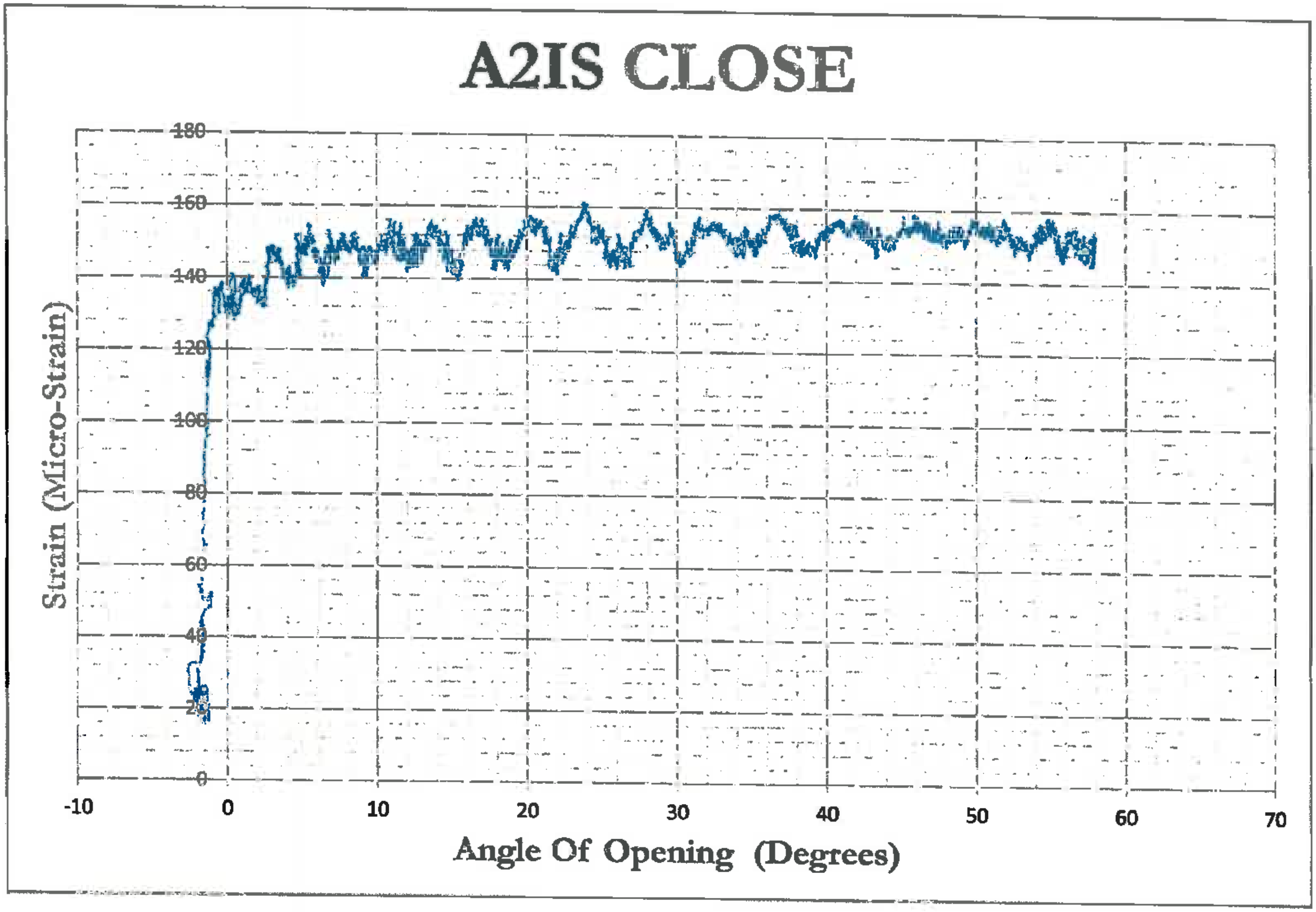
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



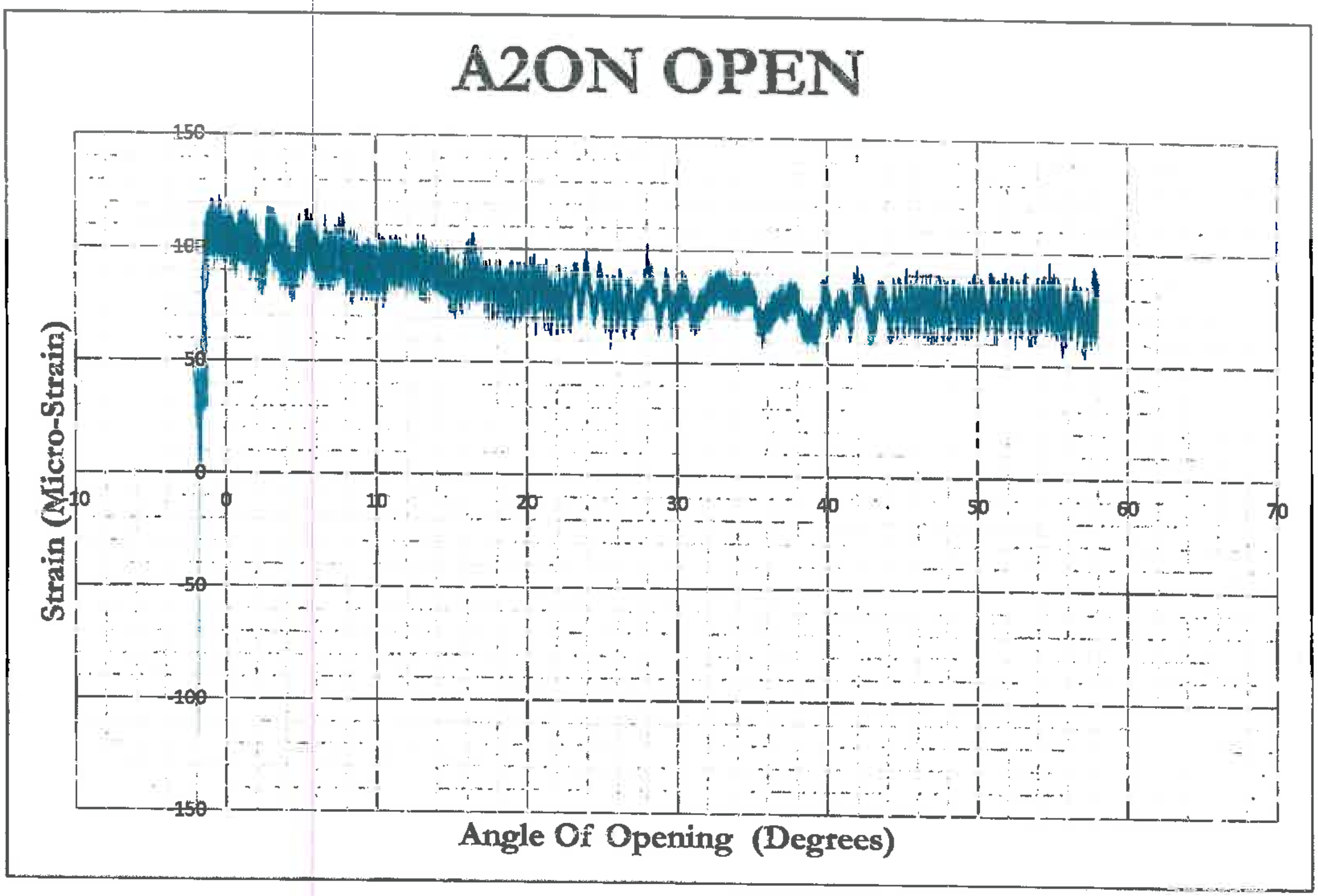
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



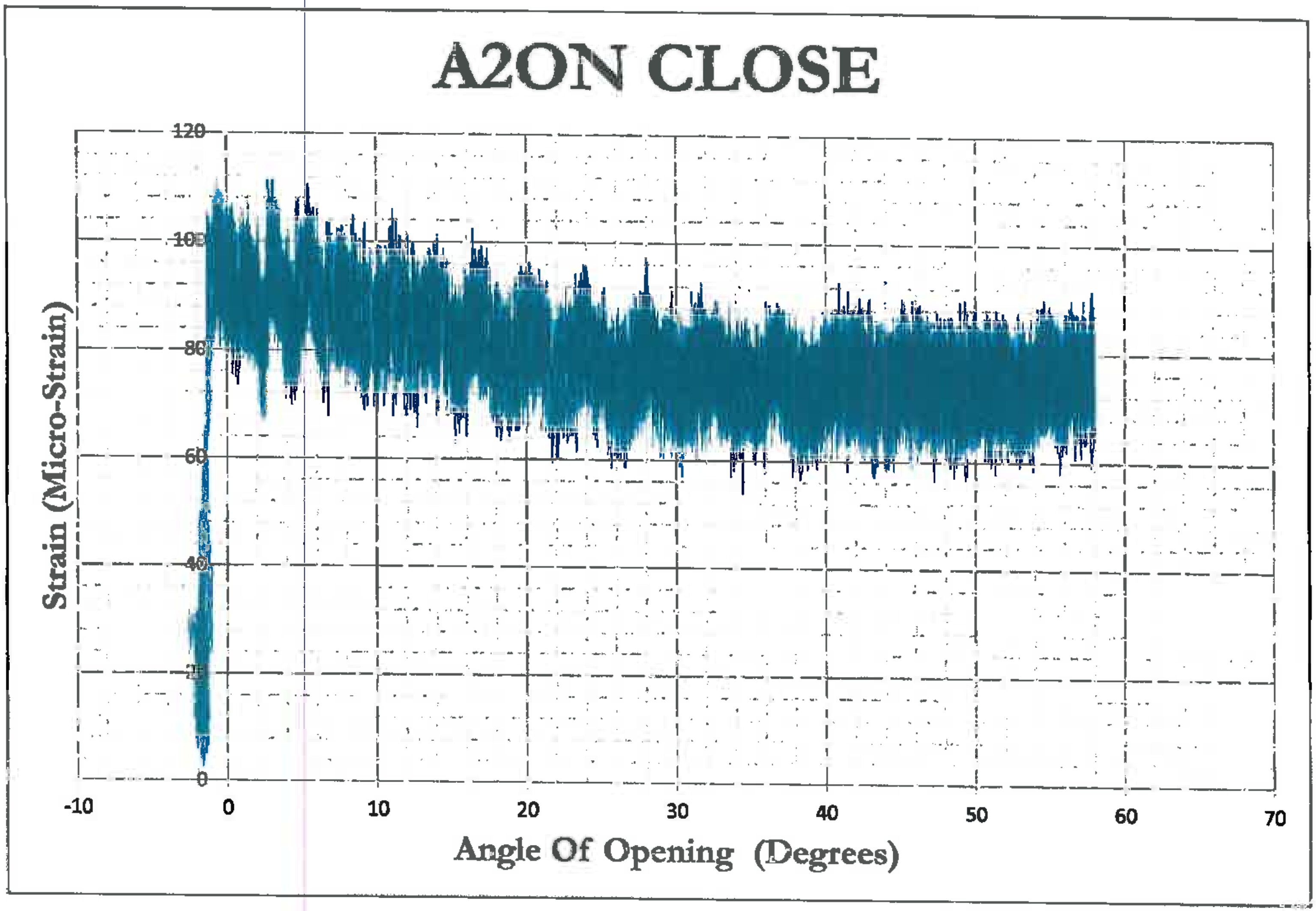
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



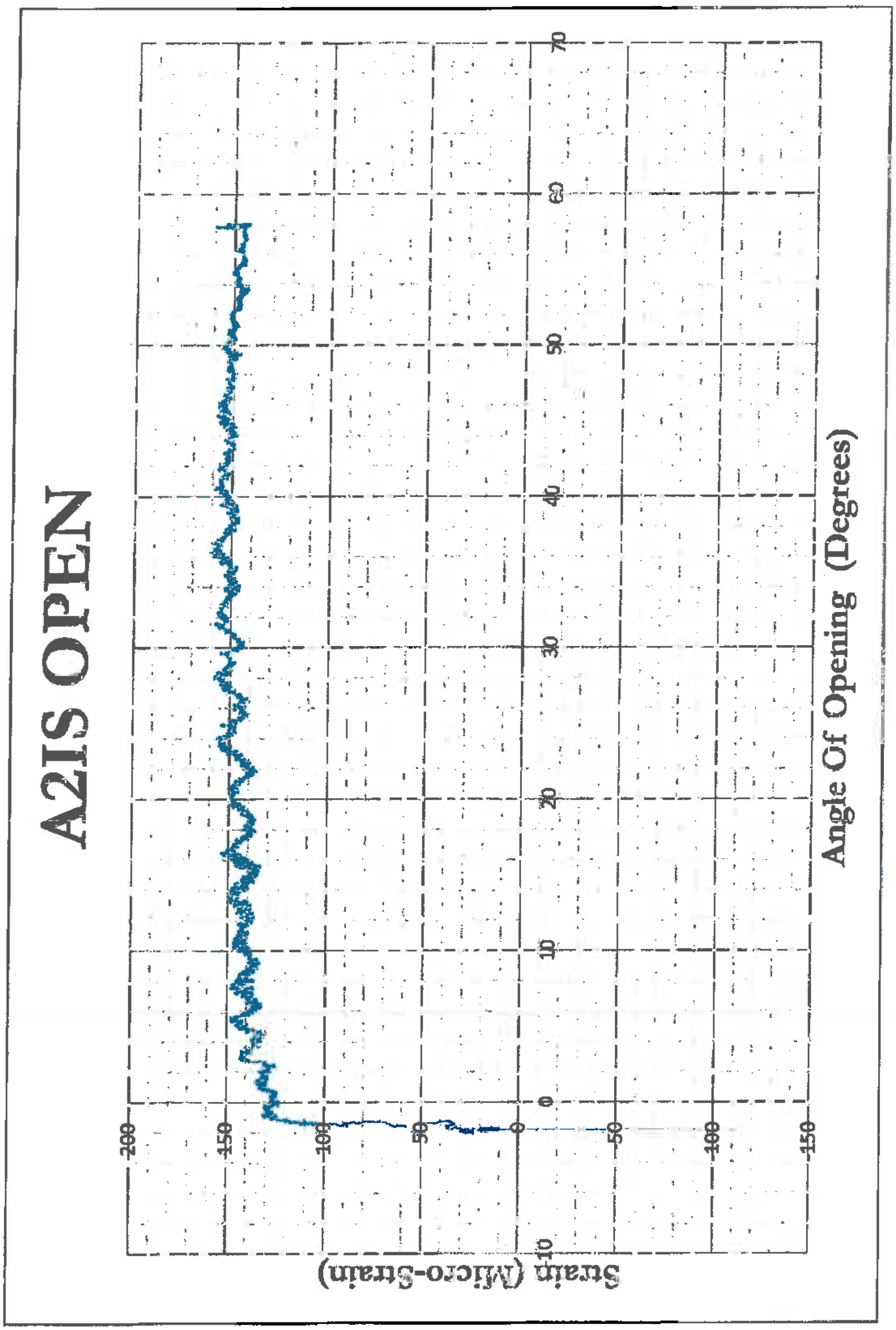
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



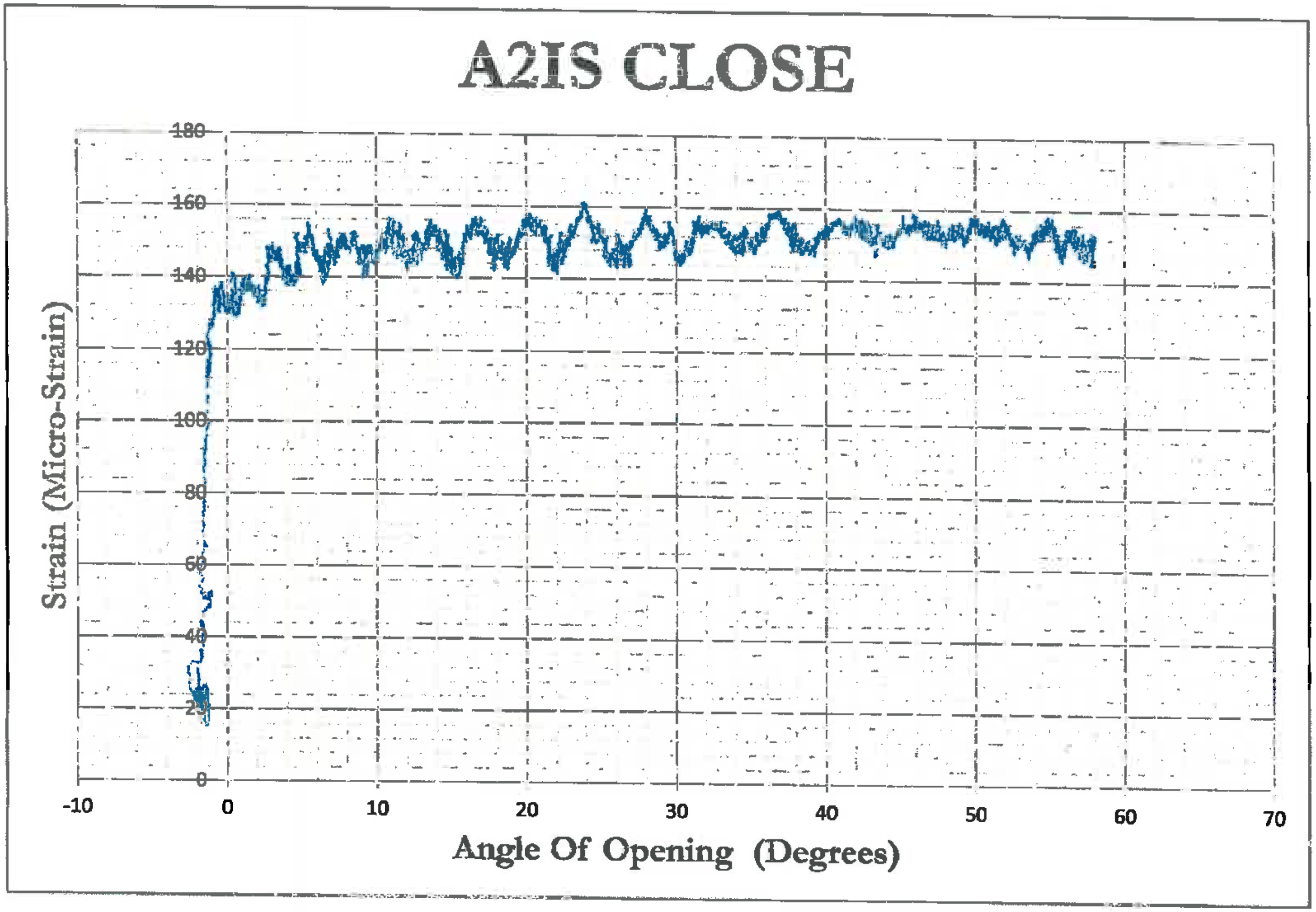
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



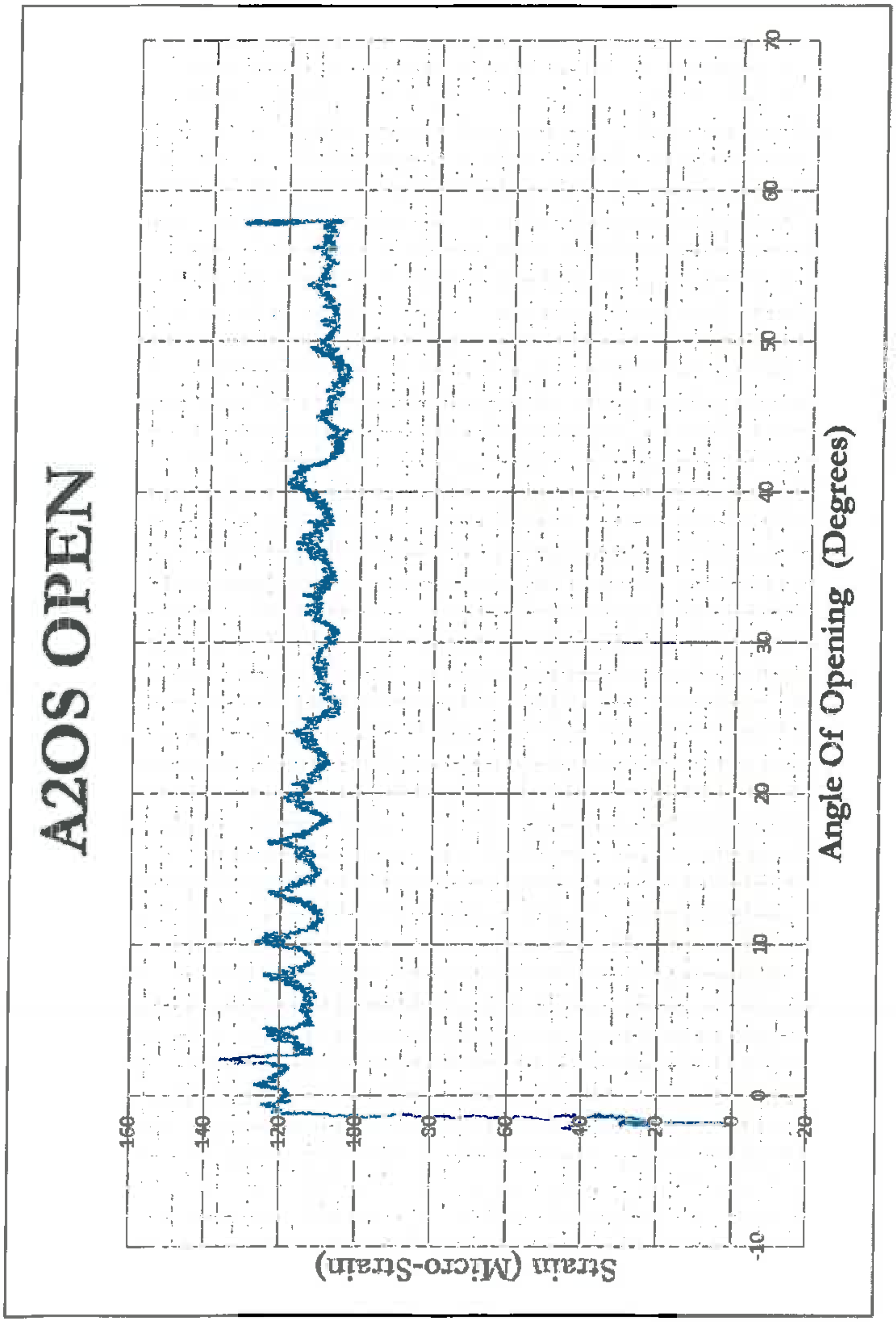
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



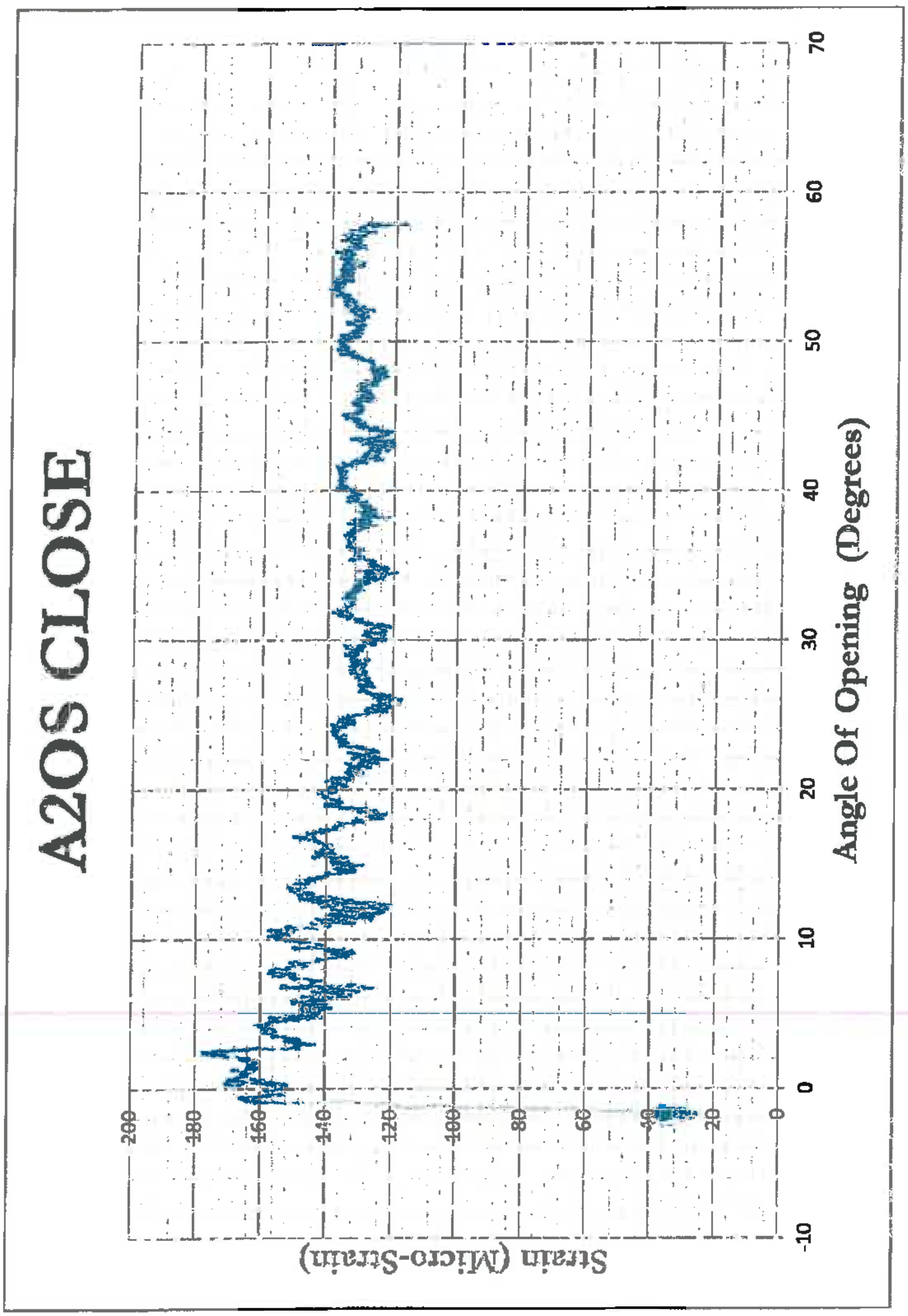
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



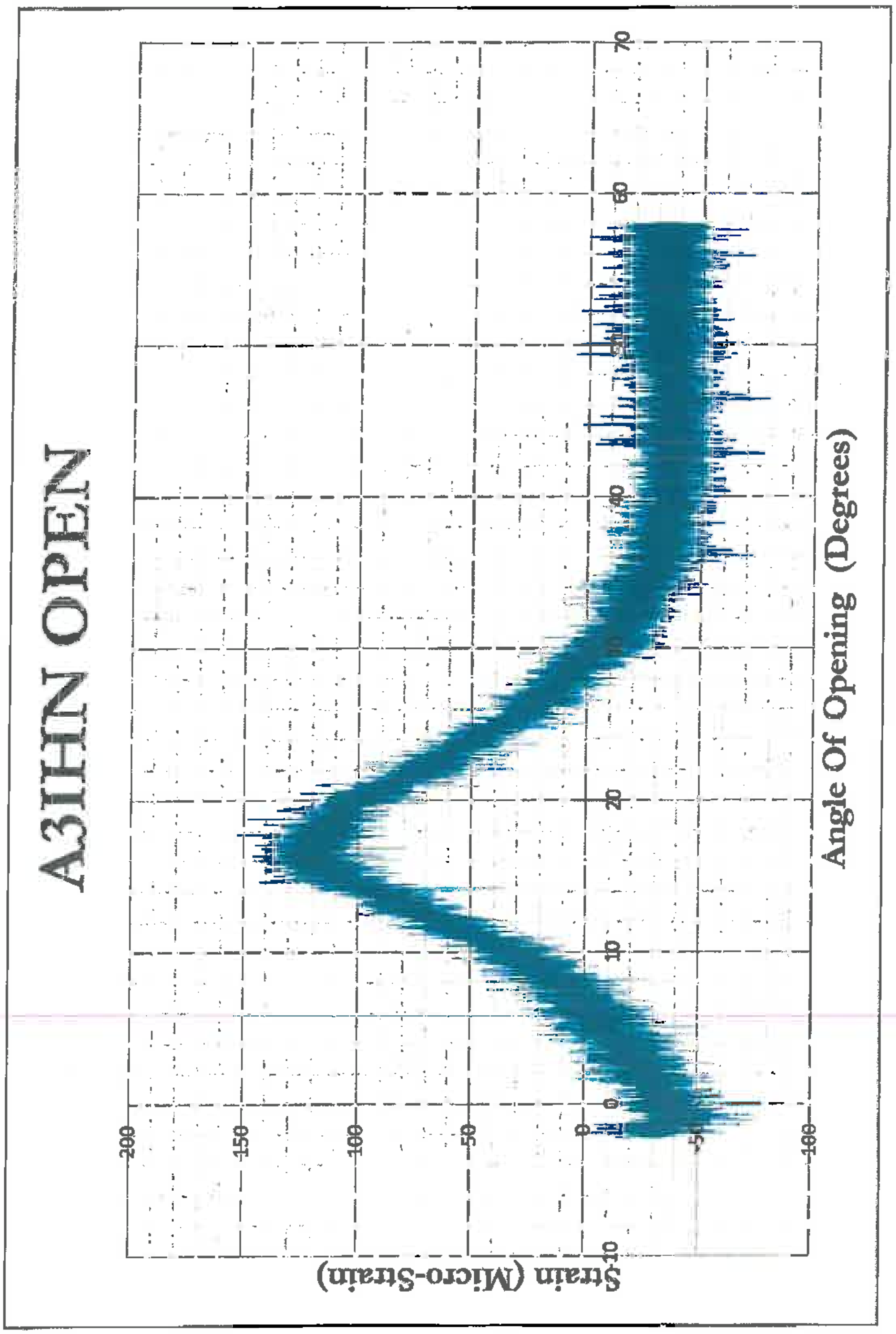
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



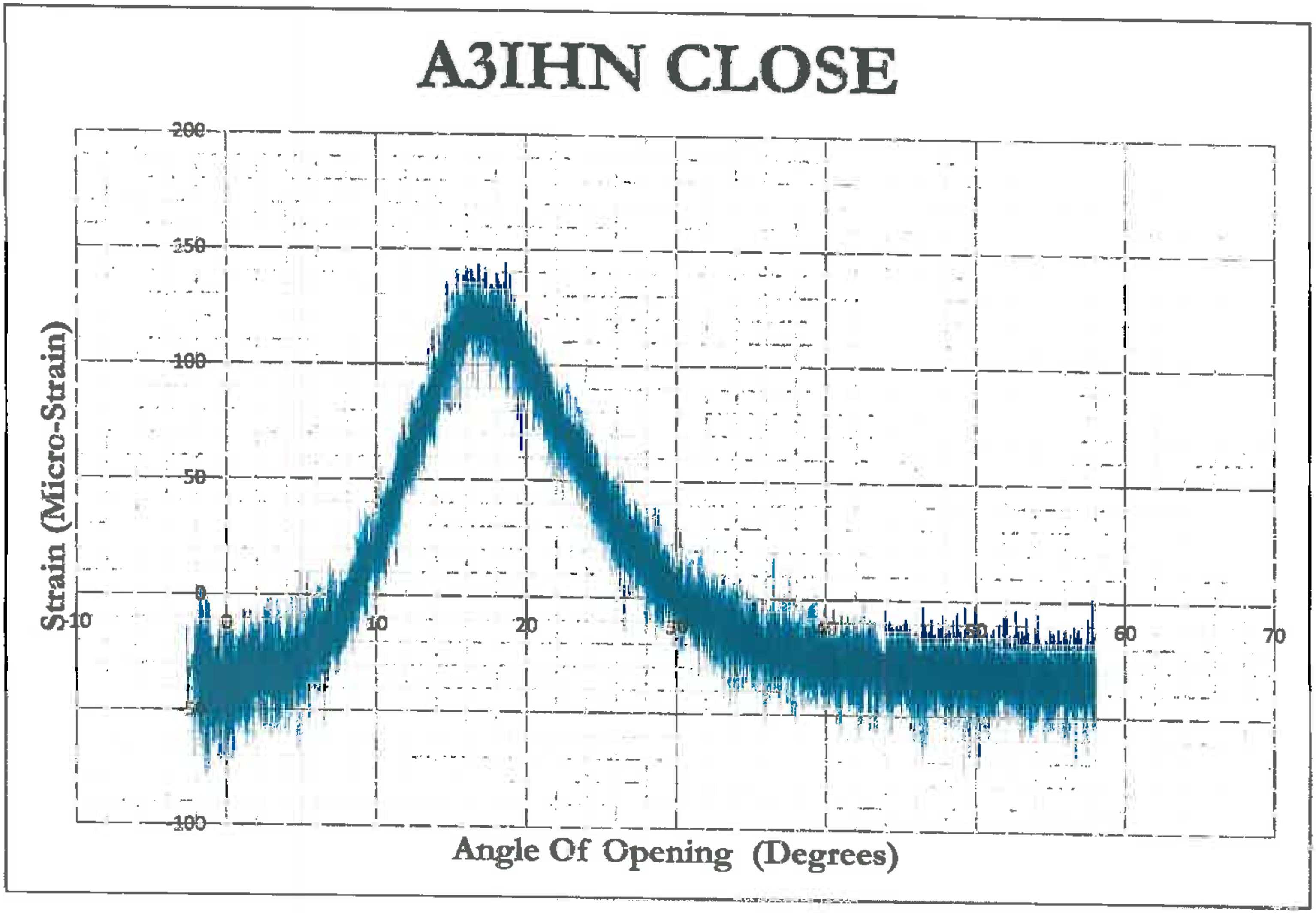
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



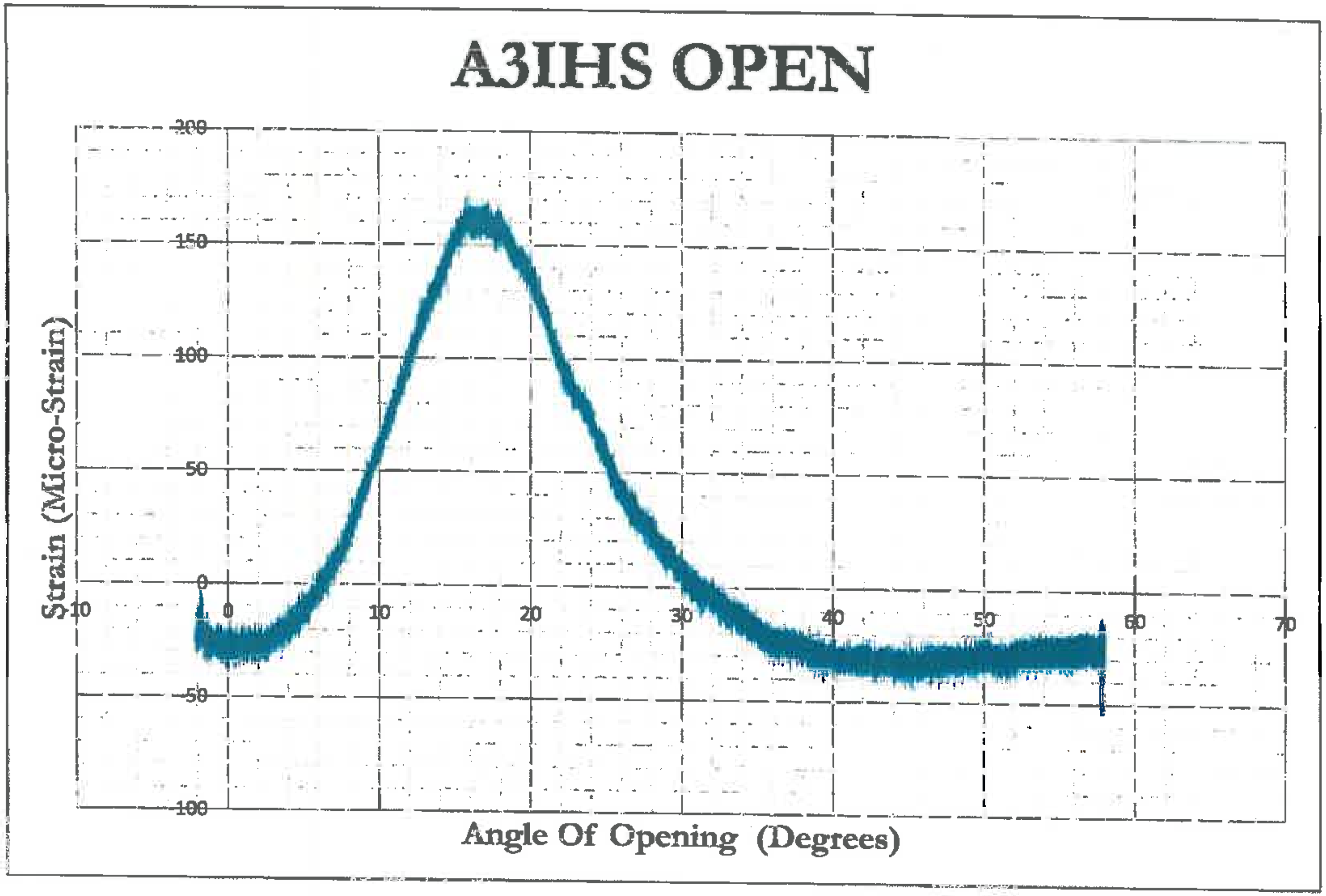
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



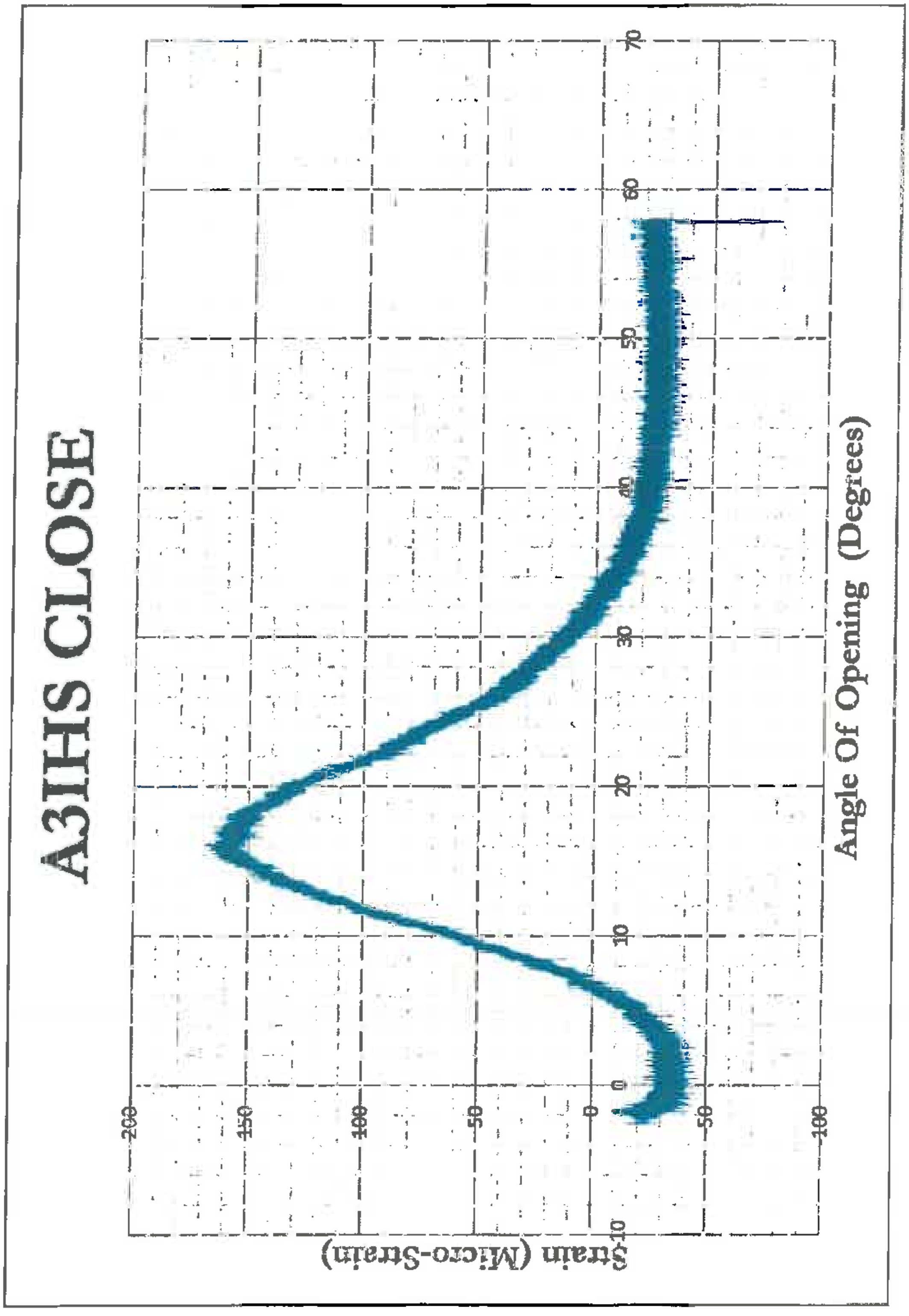
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



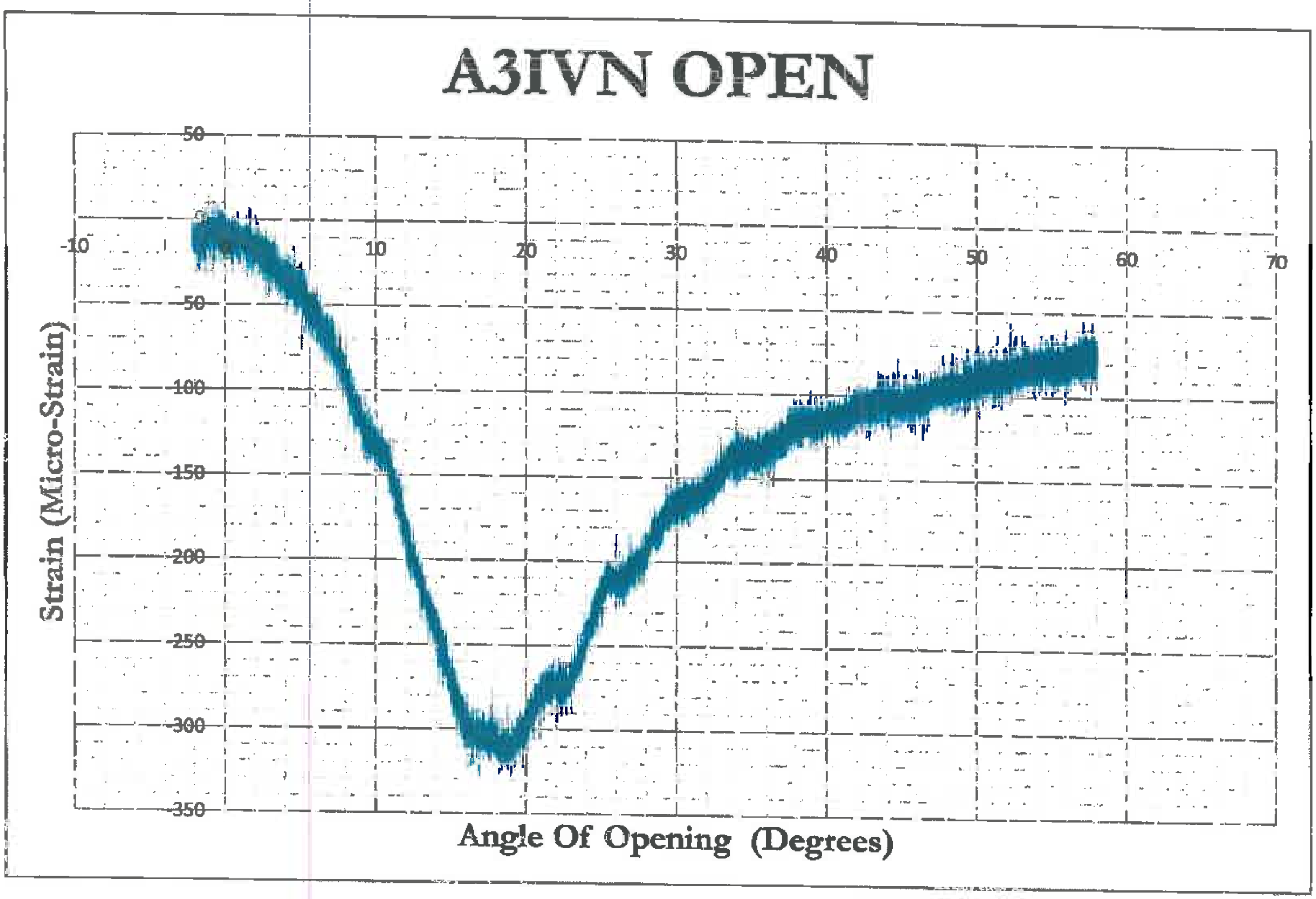
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



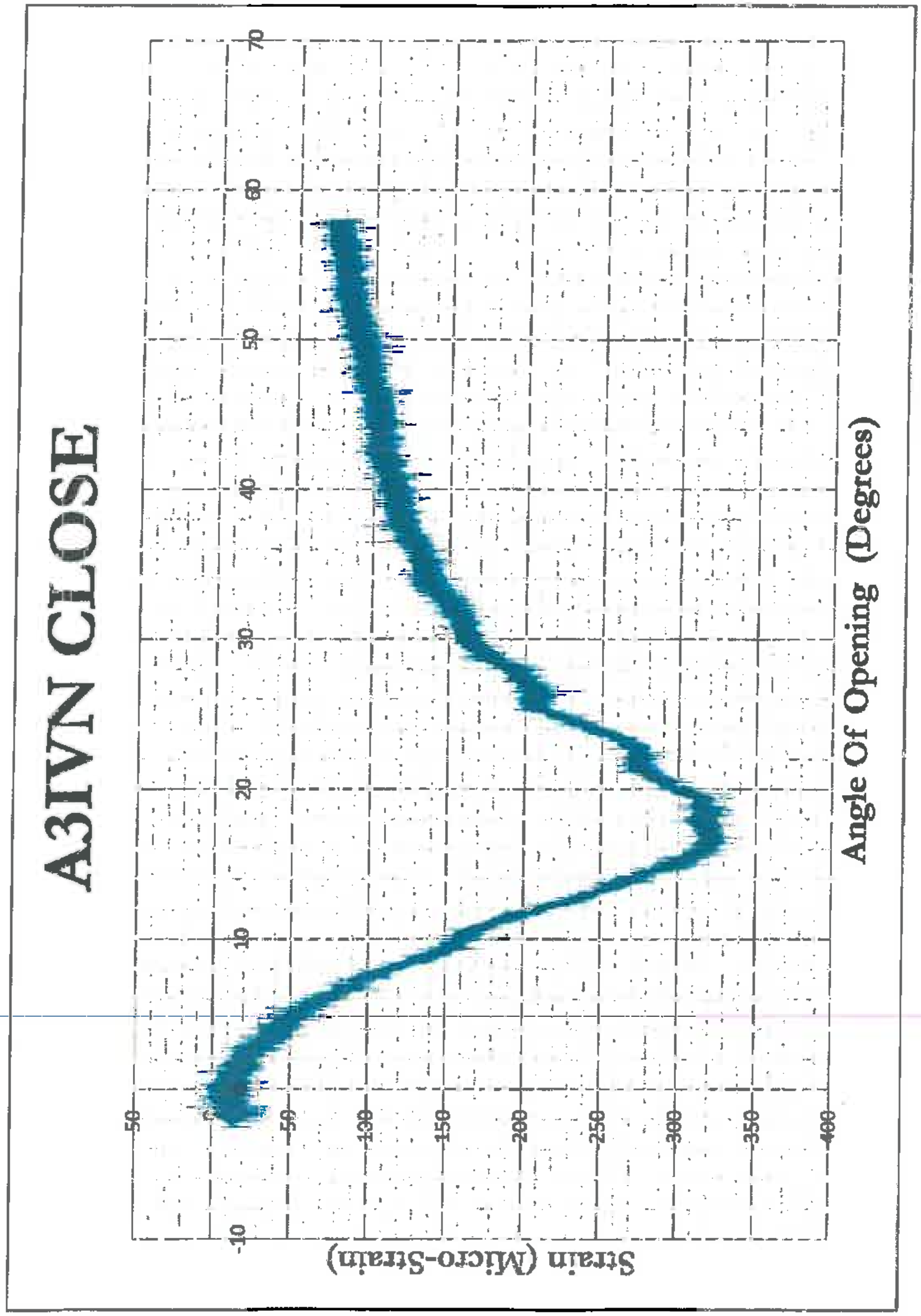
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



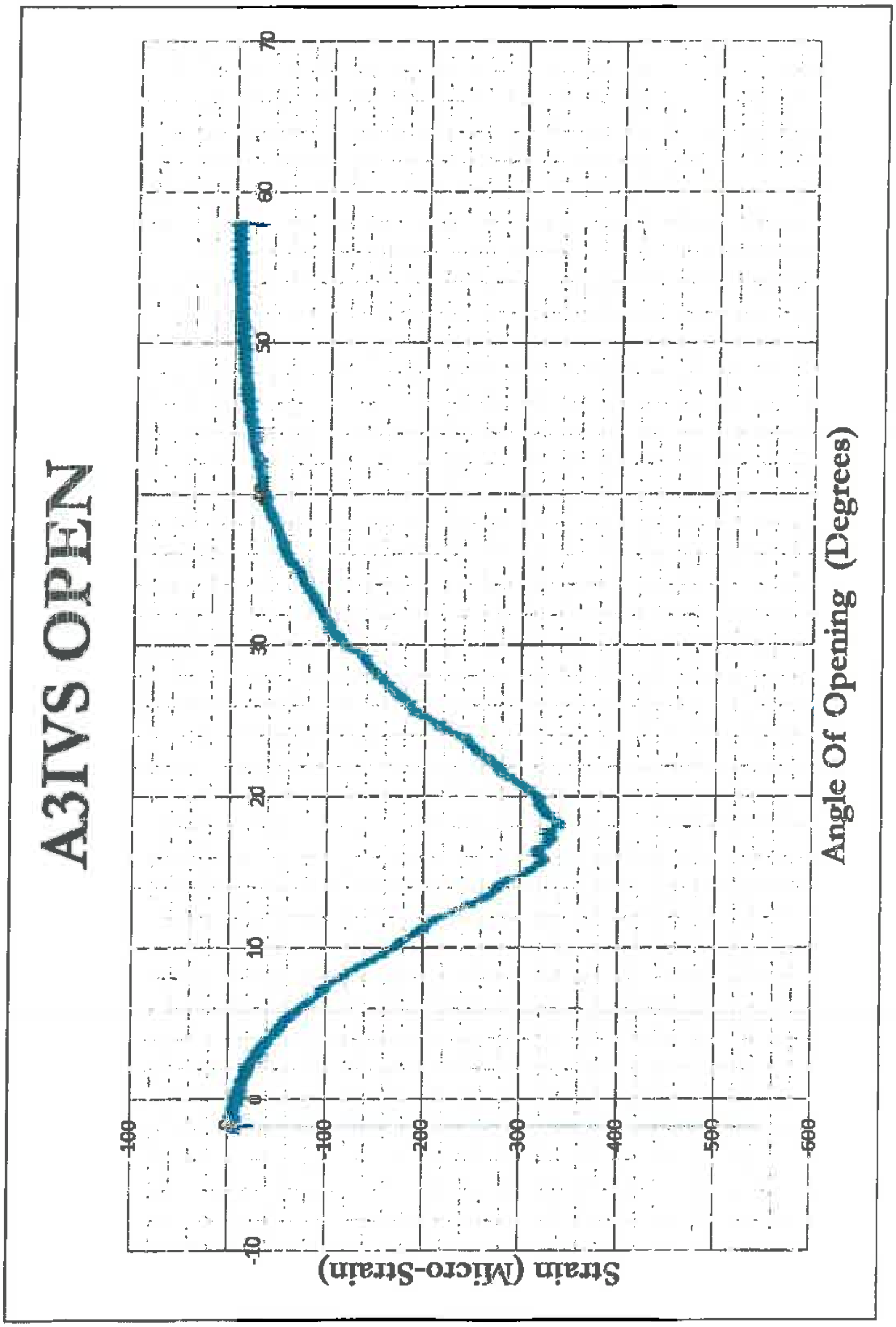
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3

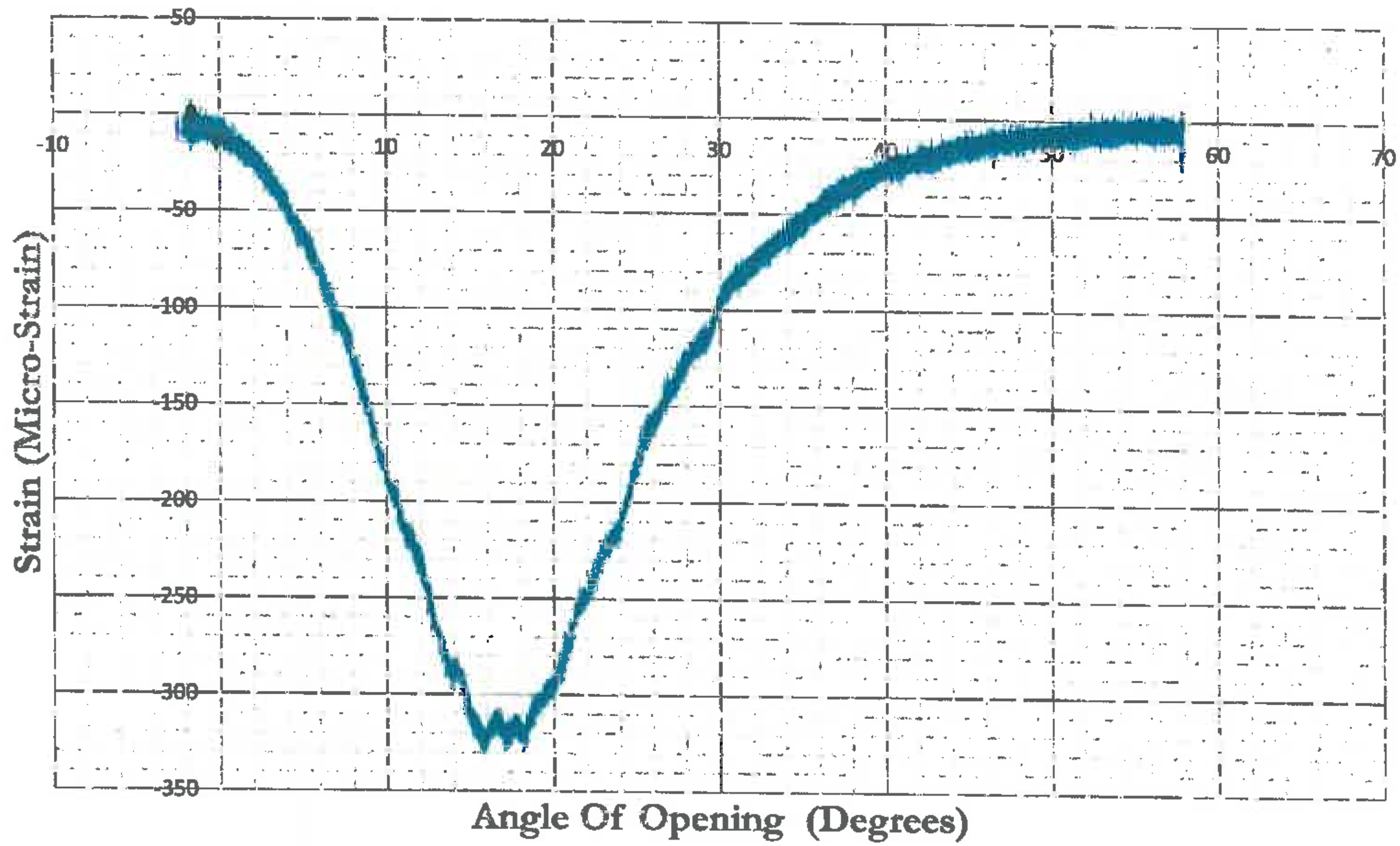


BROADWAY BRIDGE - 02720.03
WEST BRIDGE
TEST #3

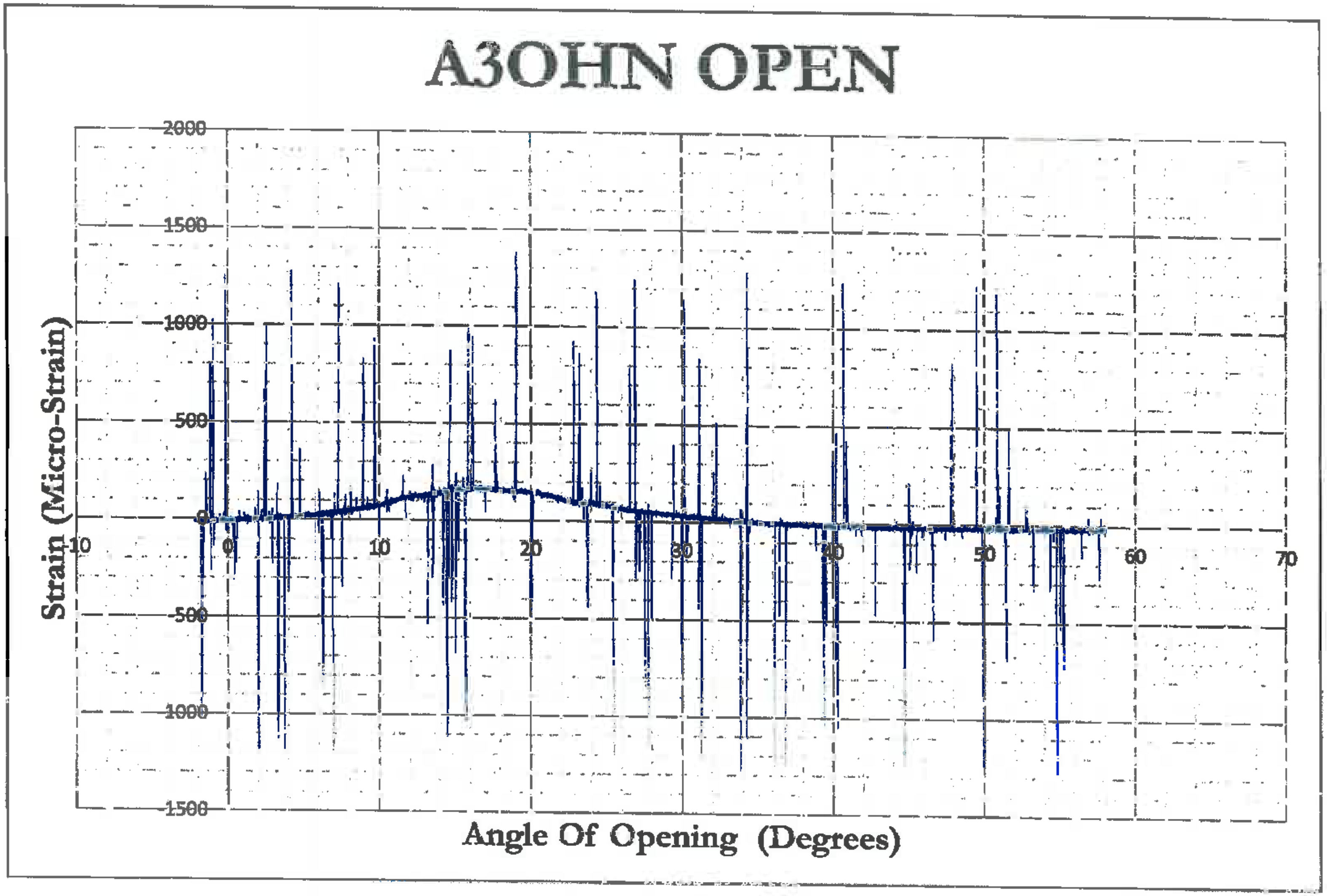


BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3

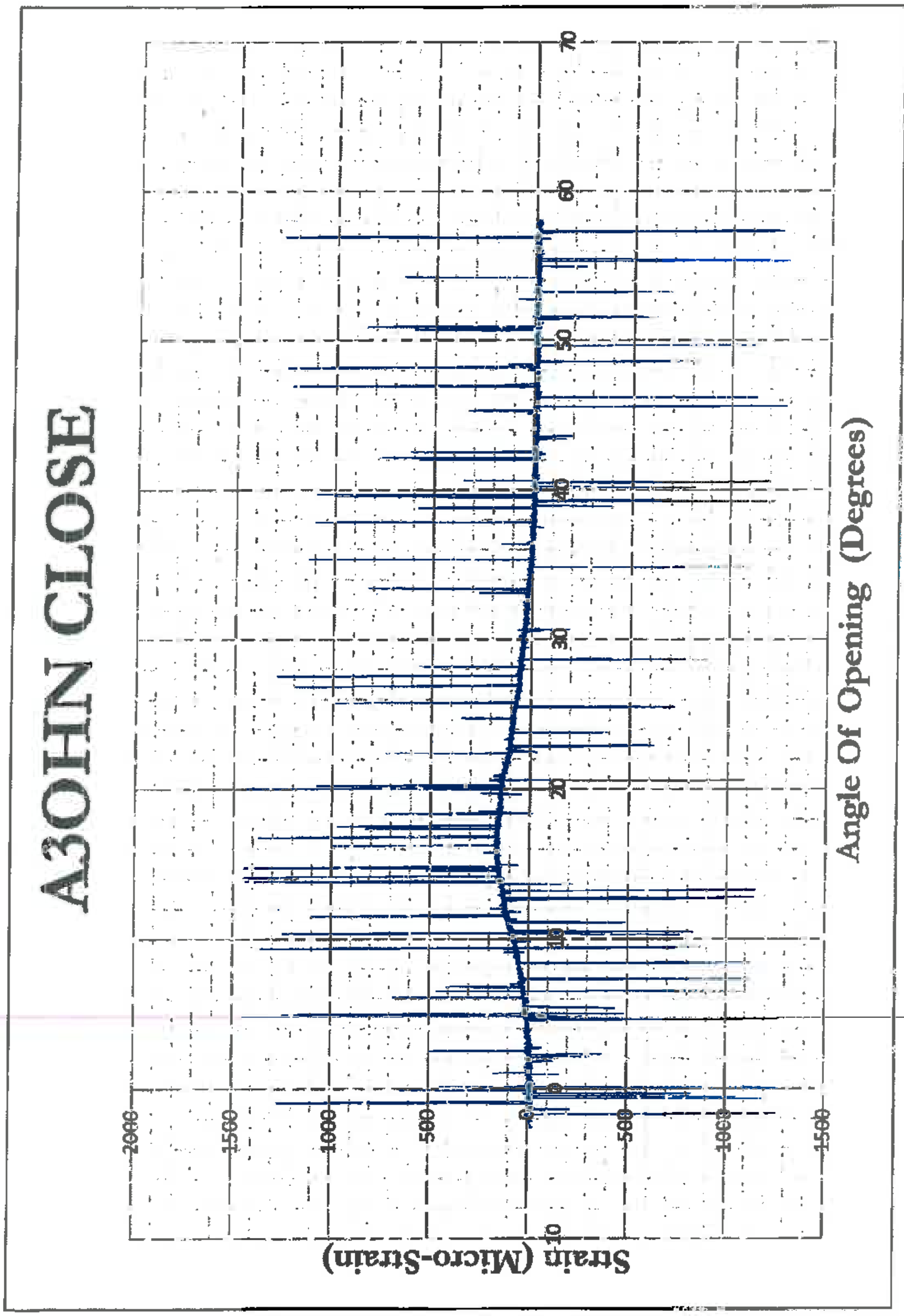
A3IVS CLOSE



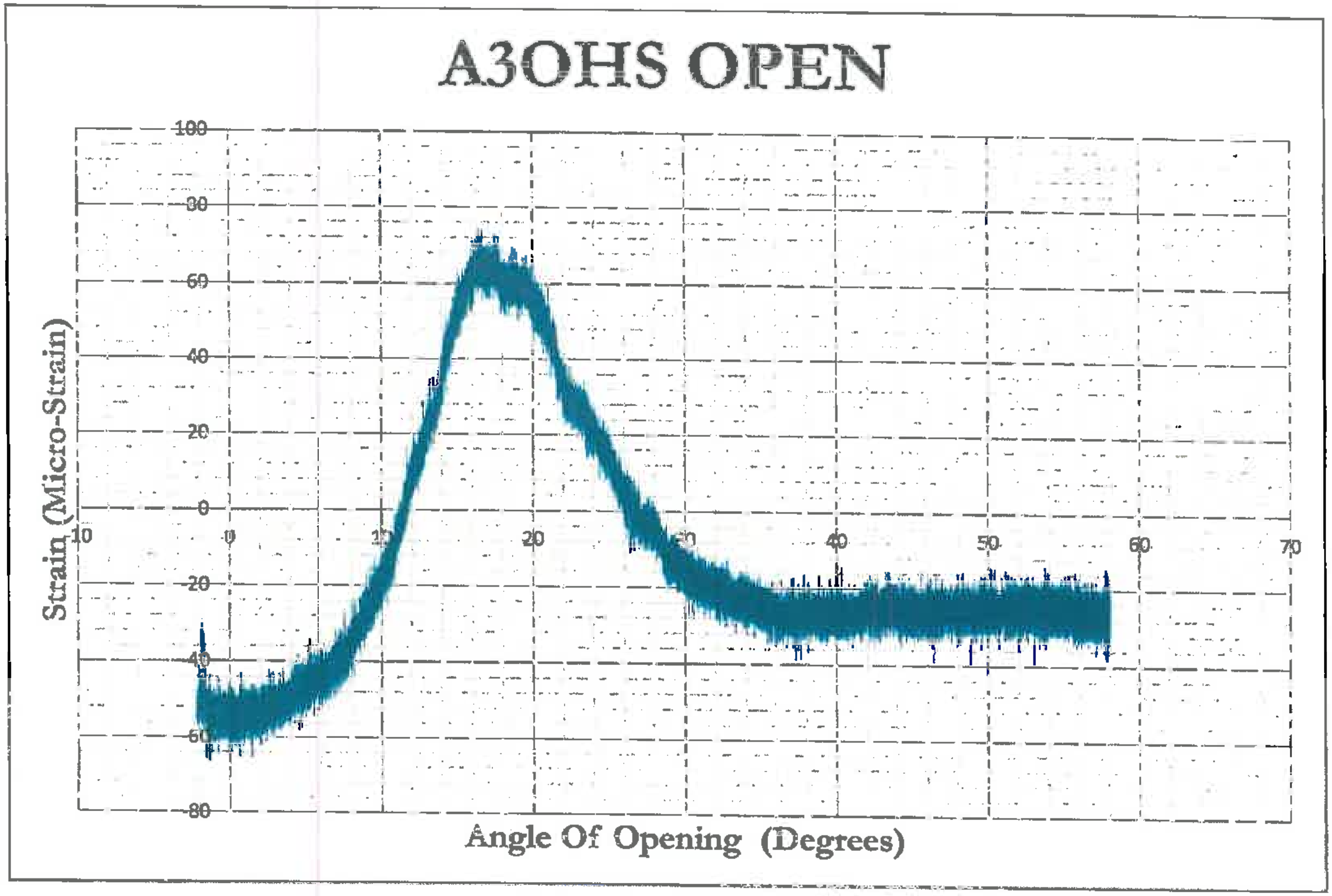
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



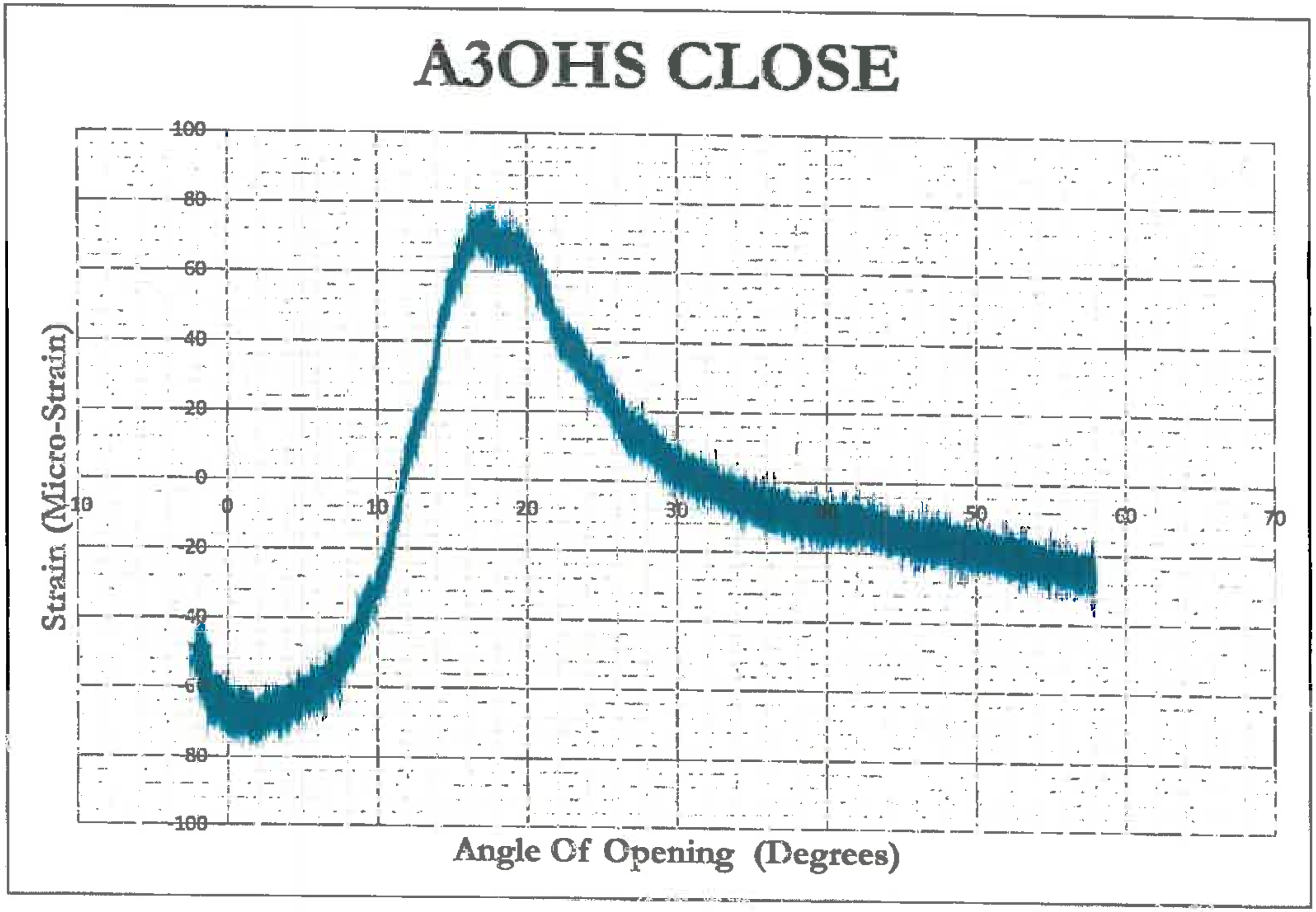
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



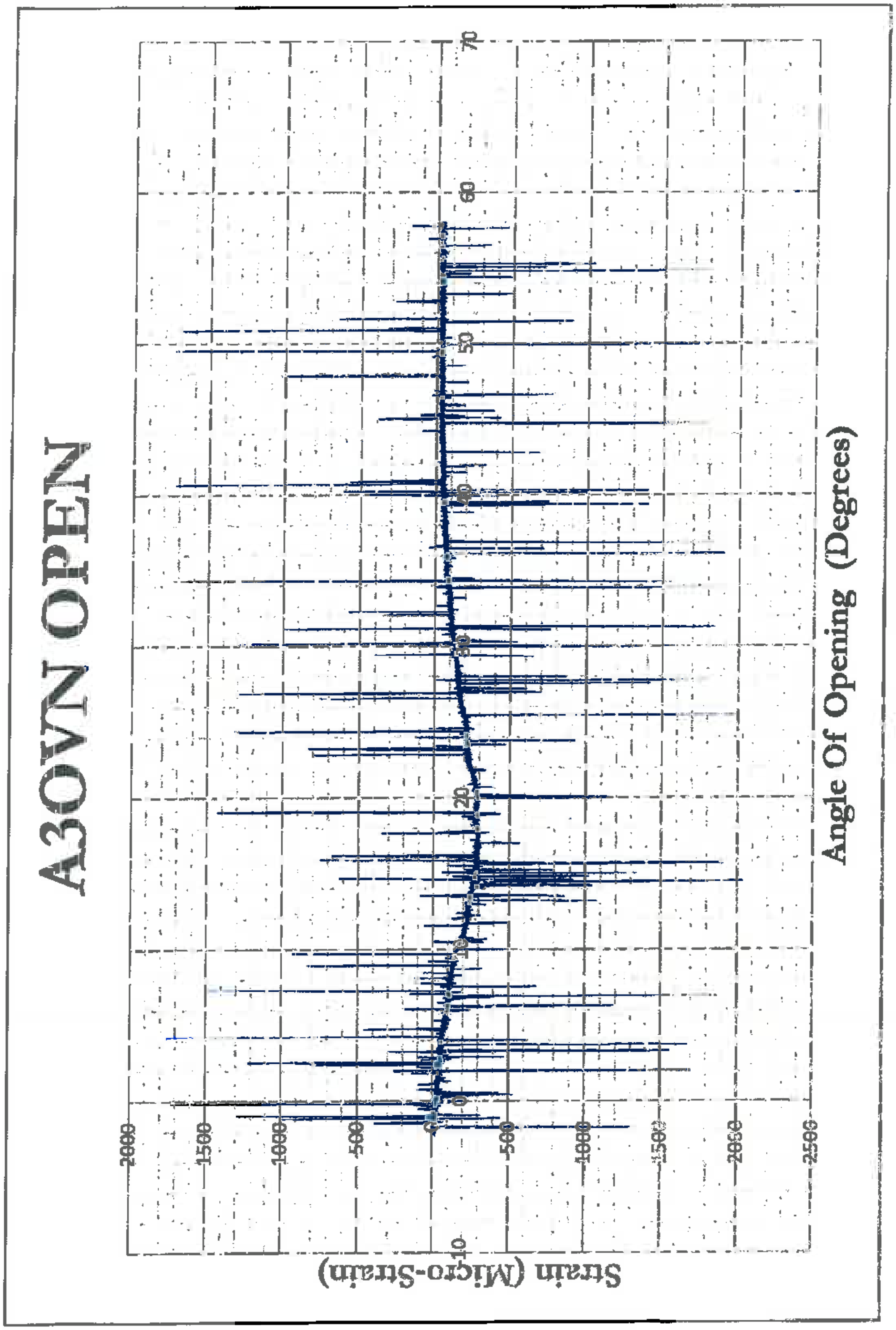
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



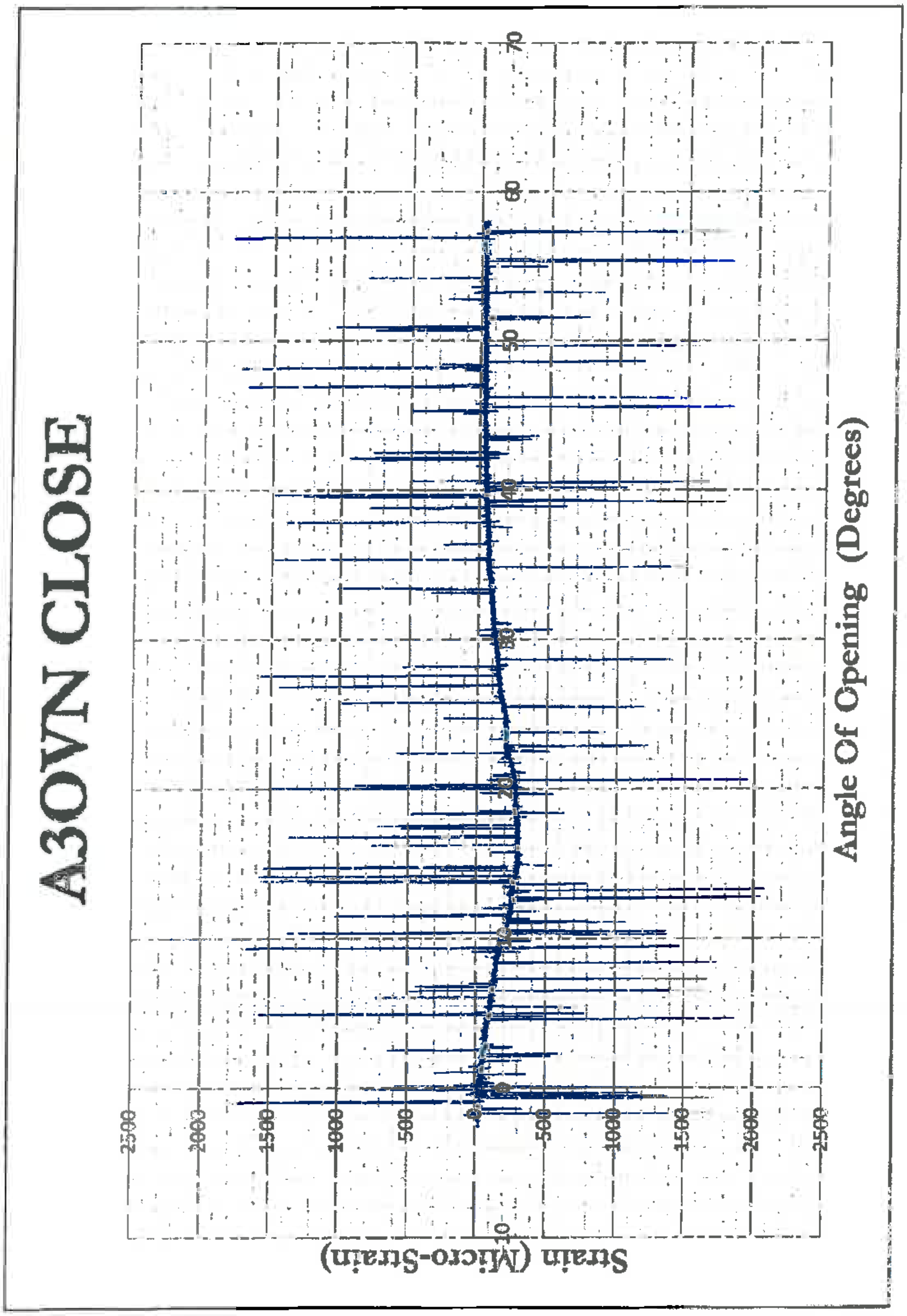
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



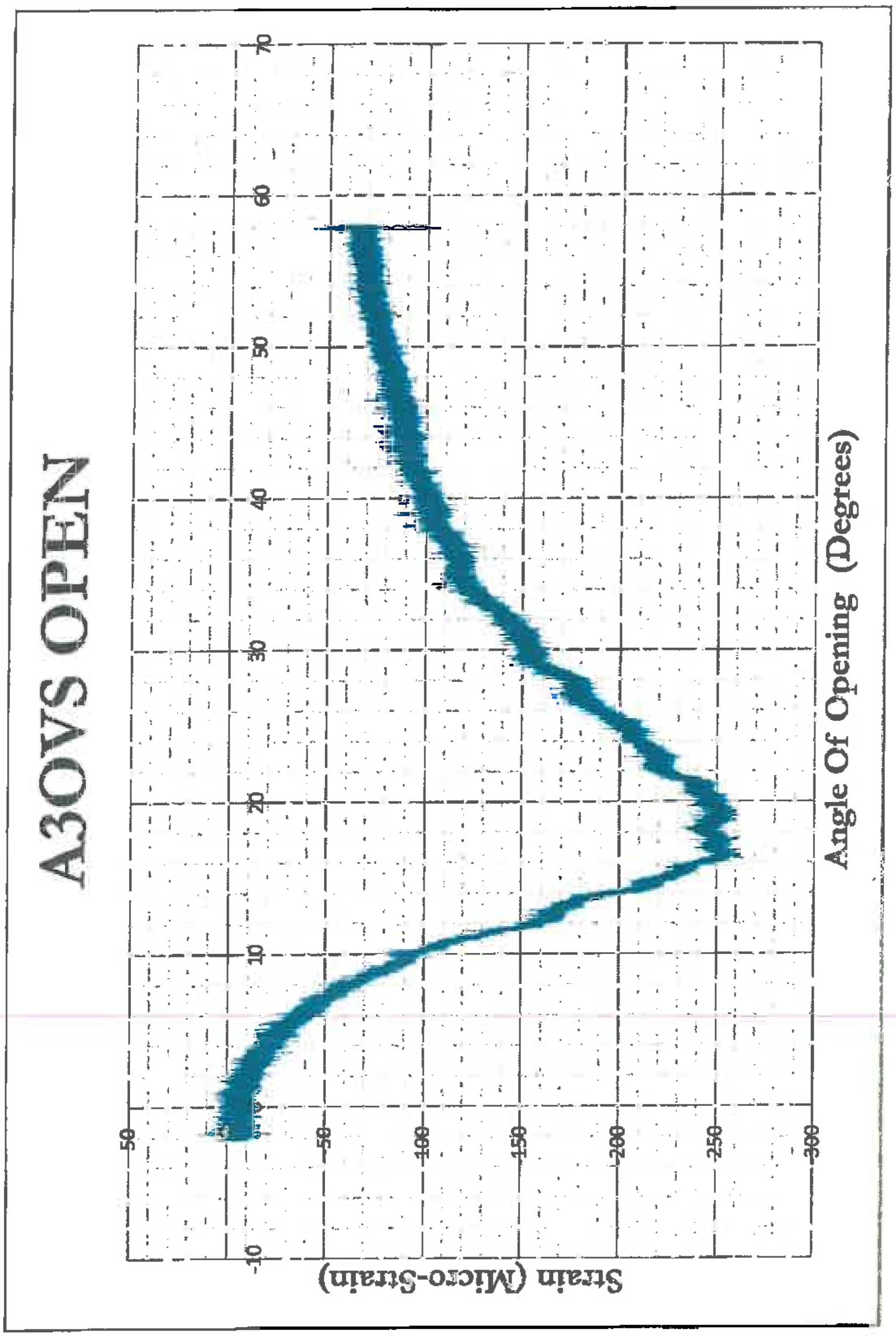
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



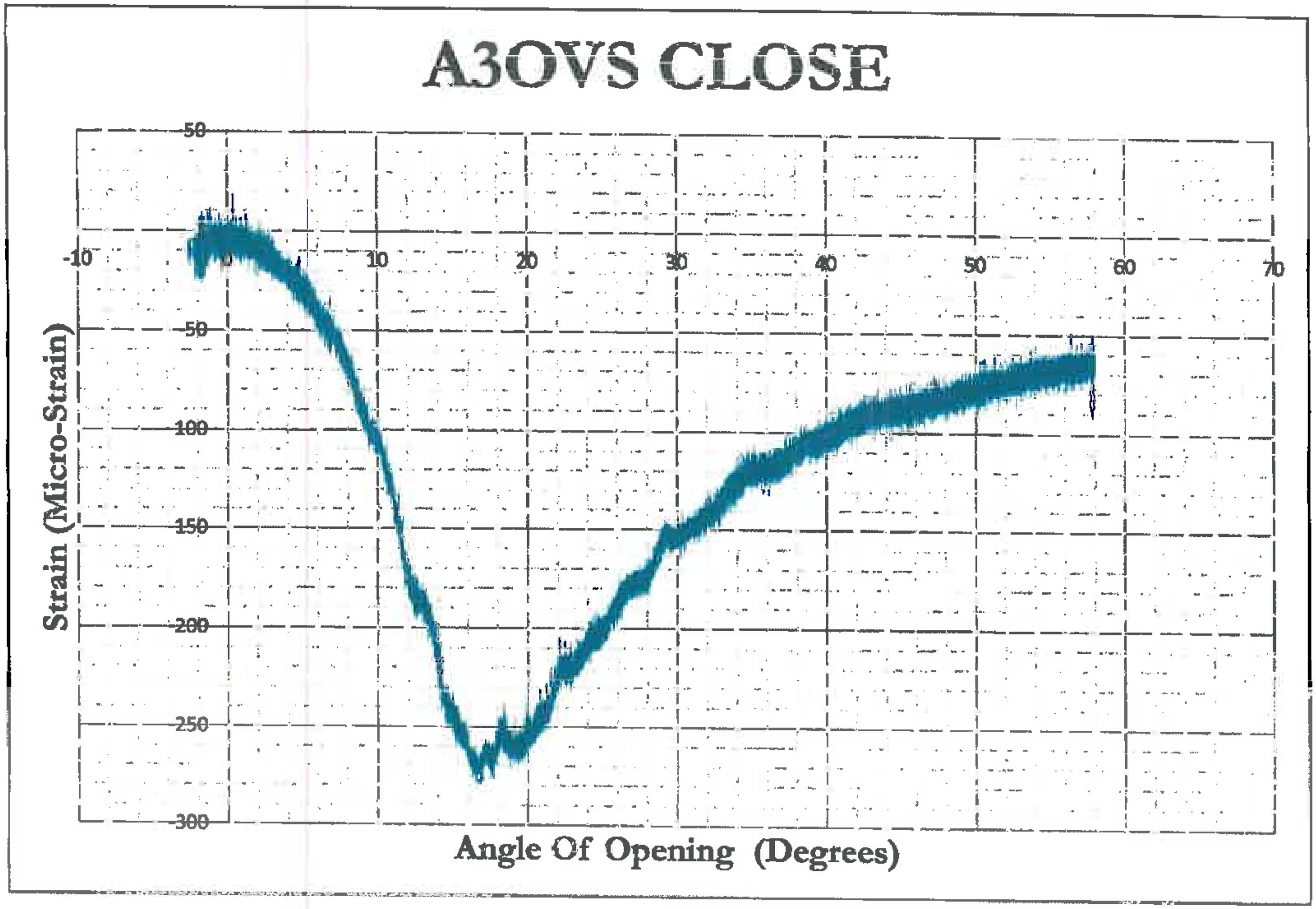
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



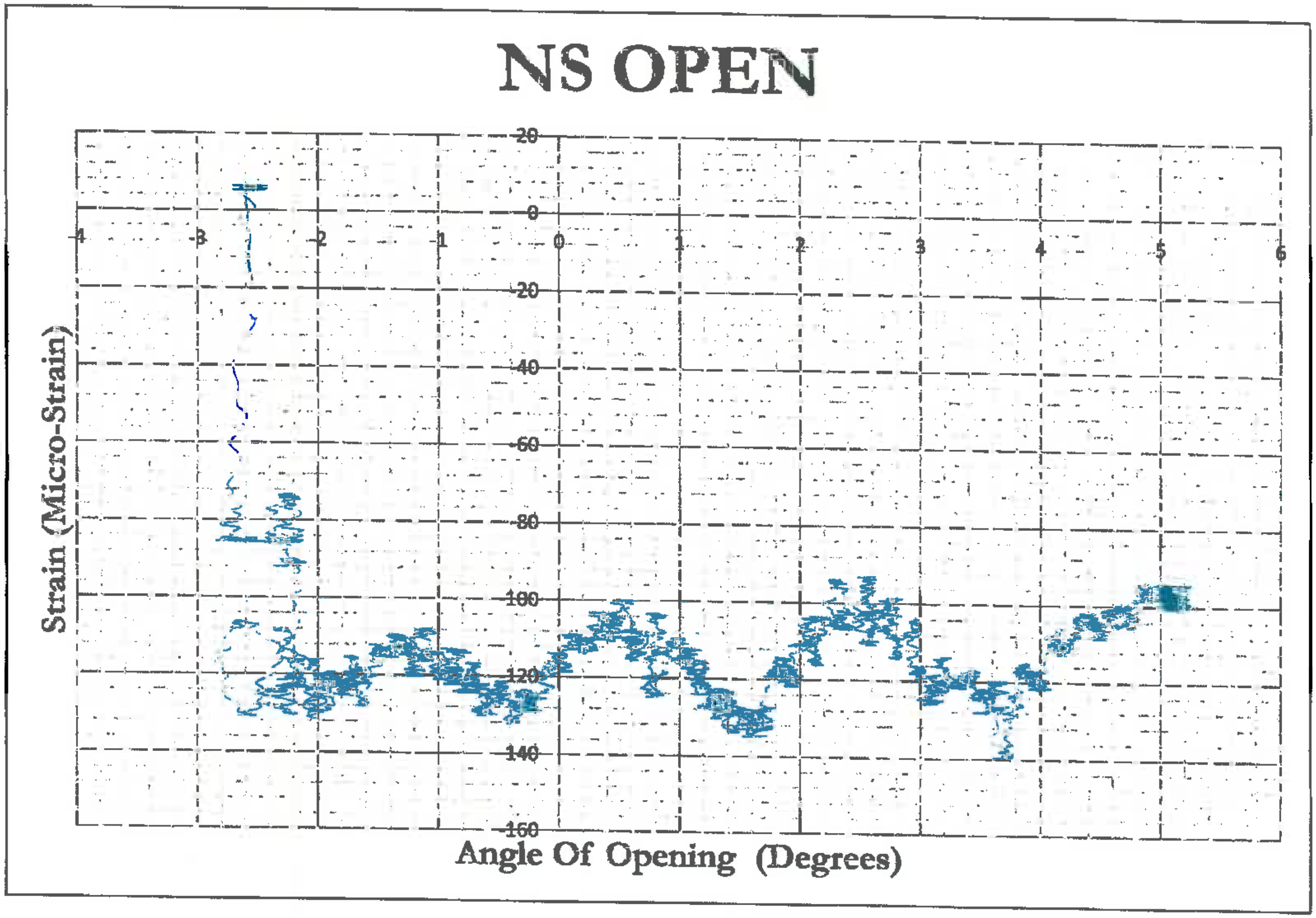
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



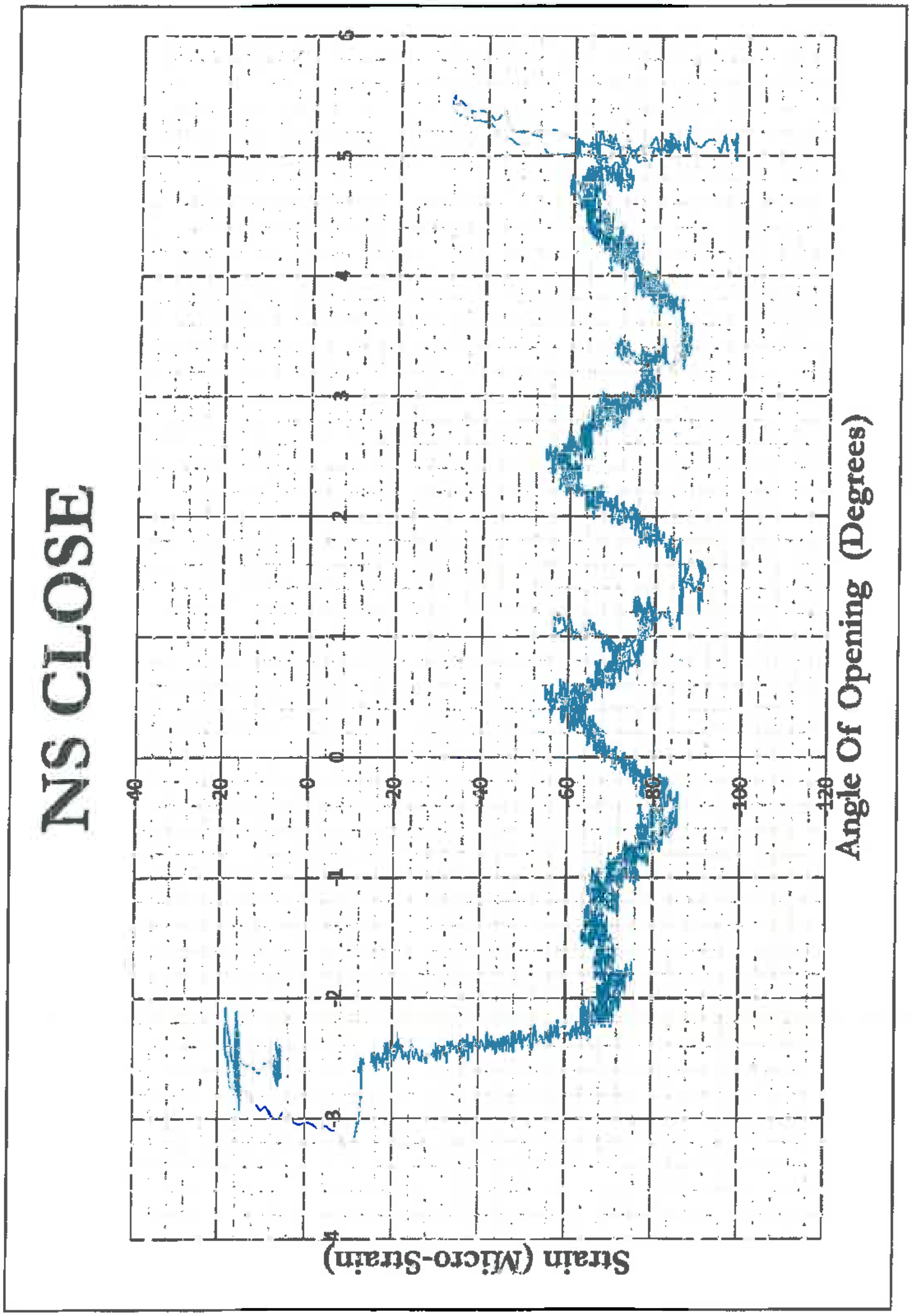
BROADWAY BRIDGE - 02720.00
WEST BRIDGE
TEST #3



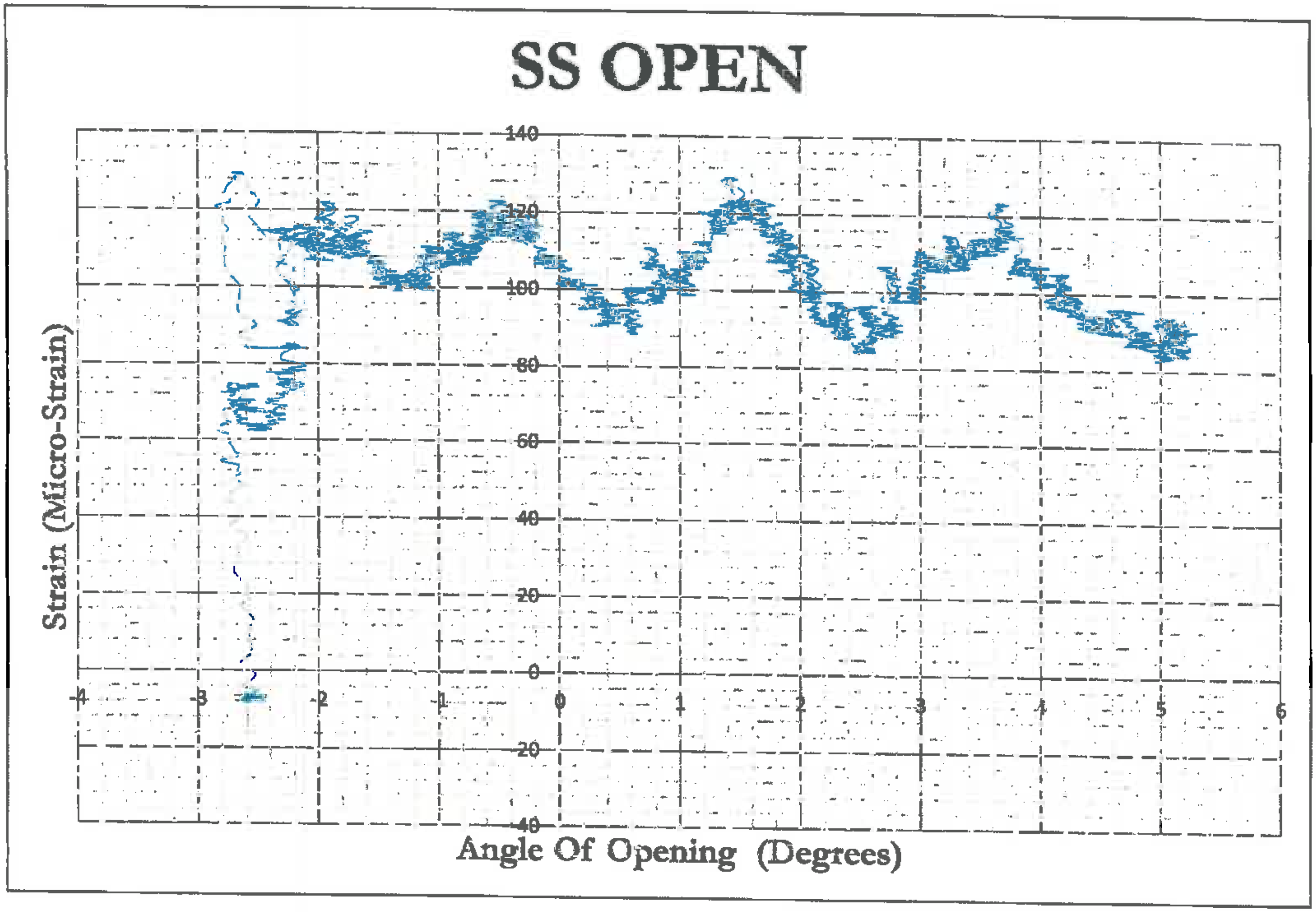
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE

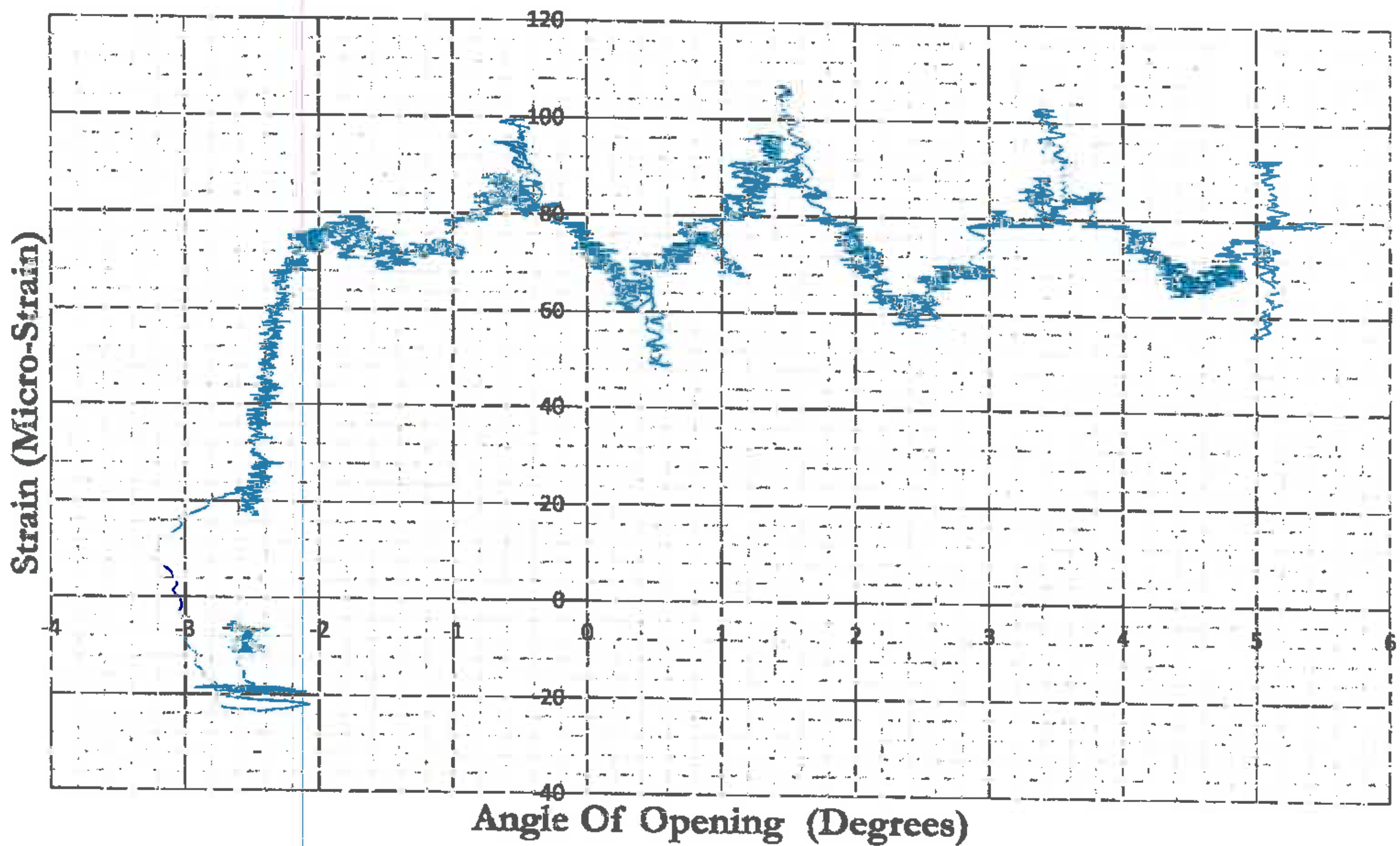


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE

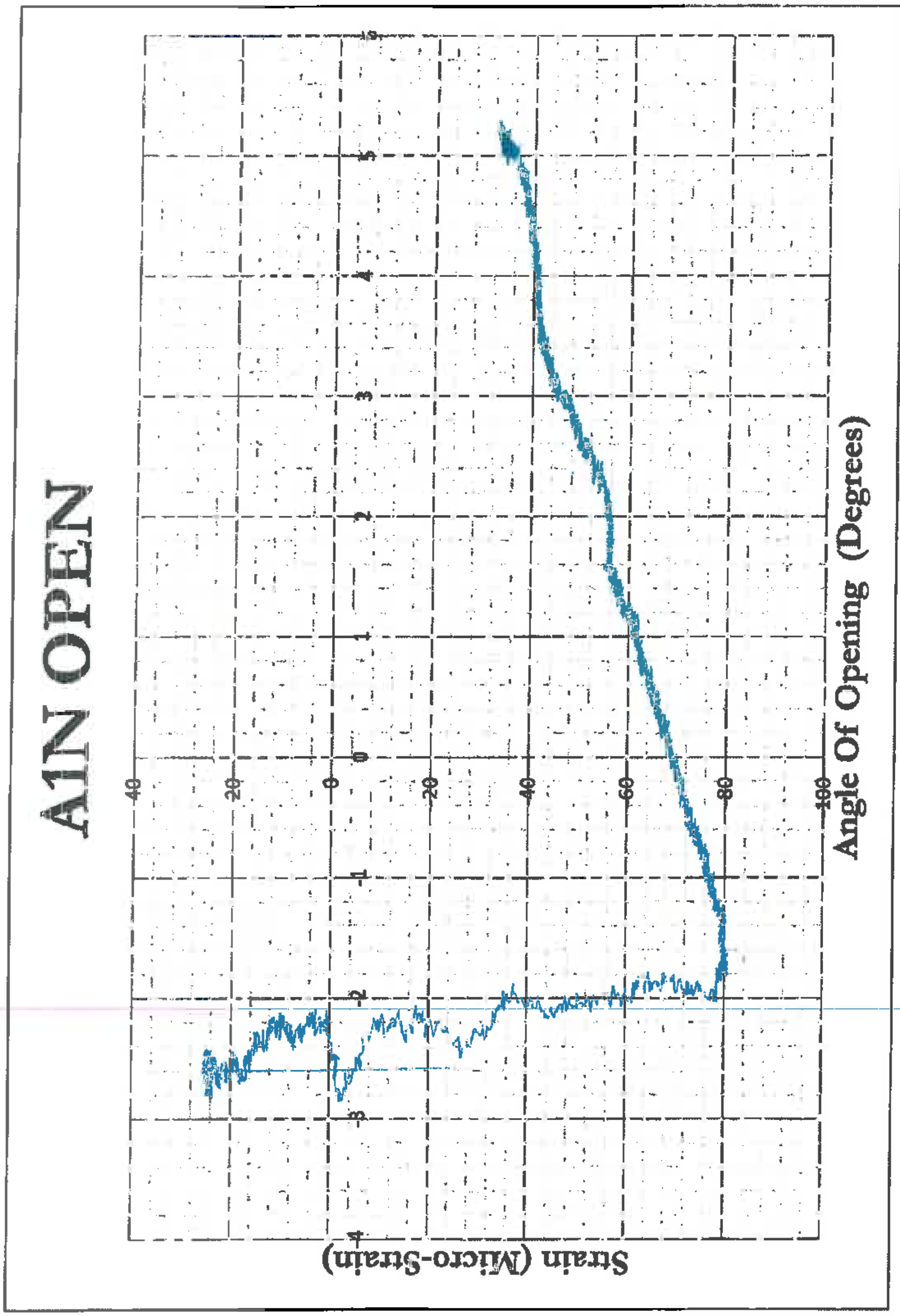


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE

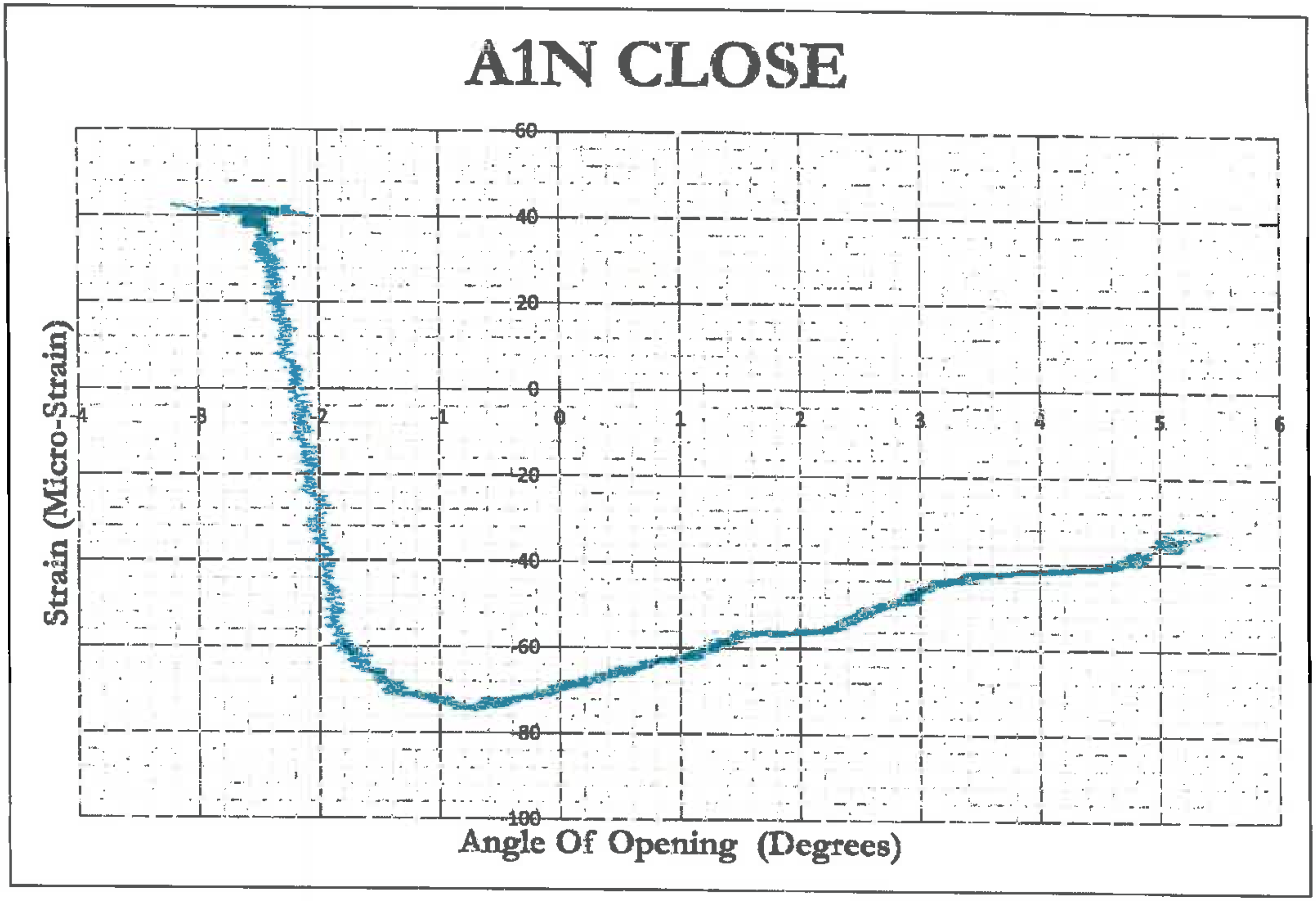
SS CLOSE



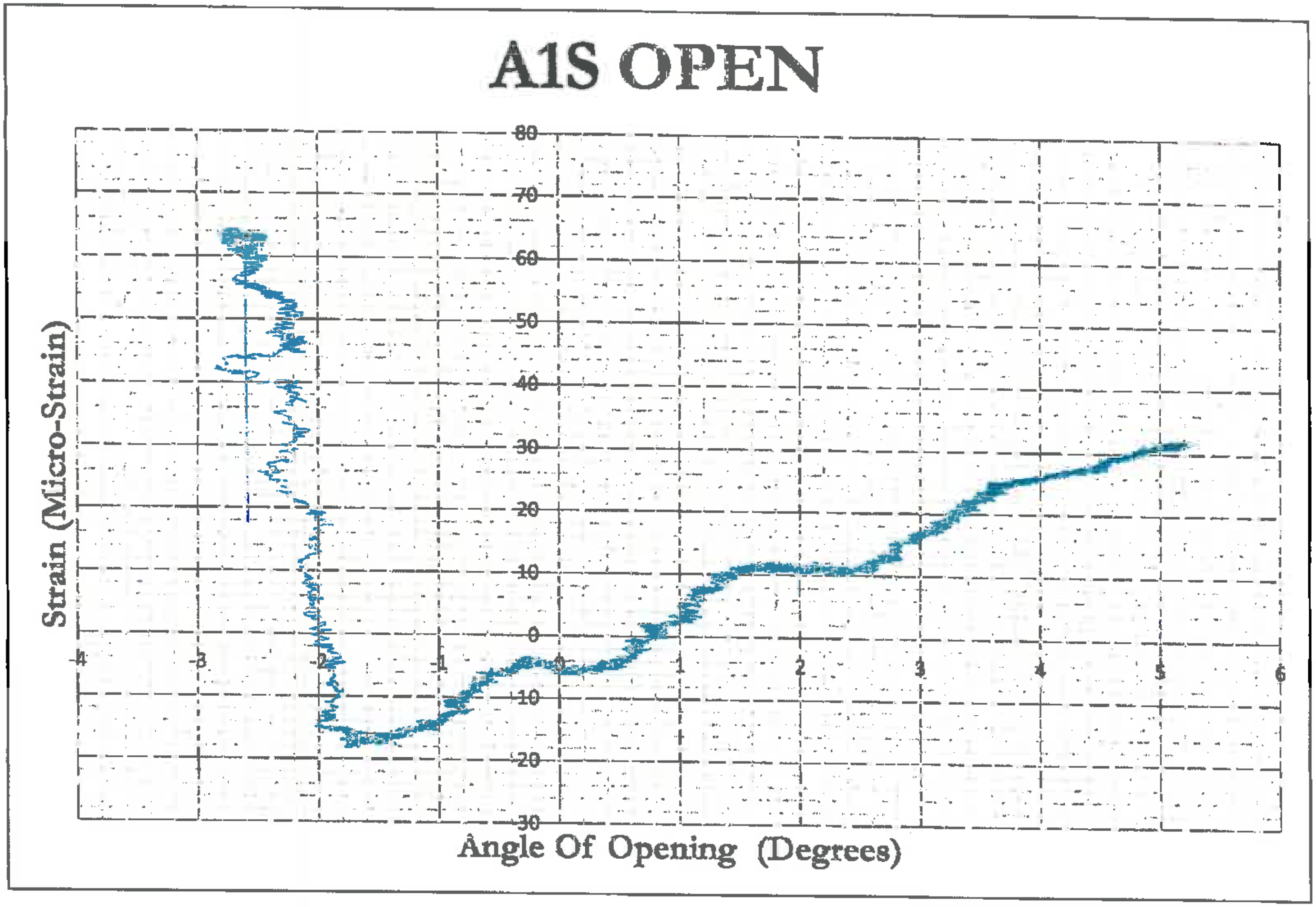
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE



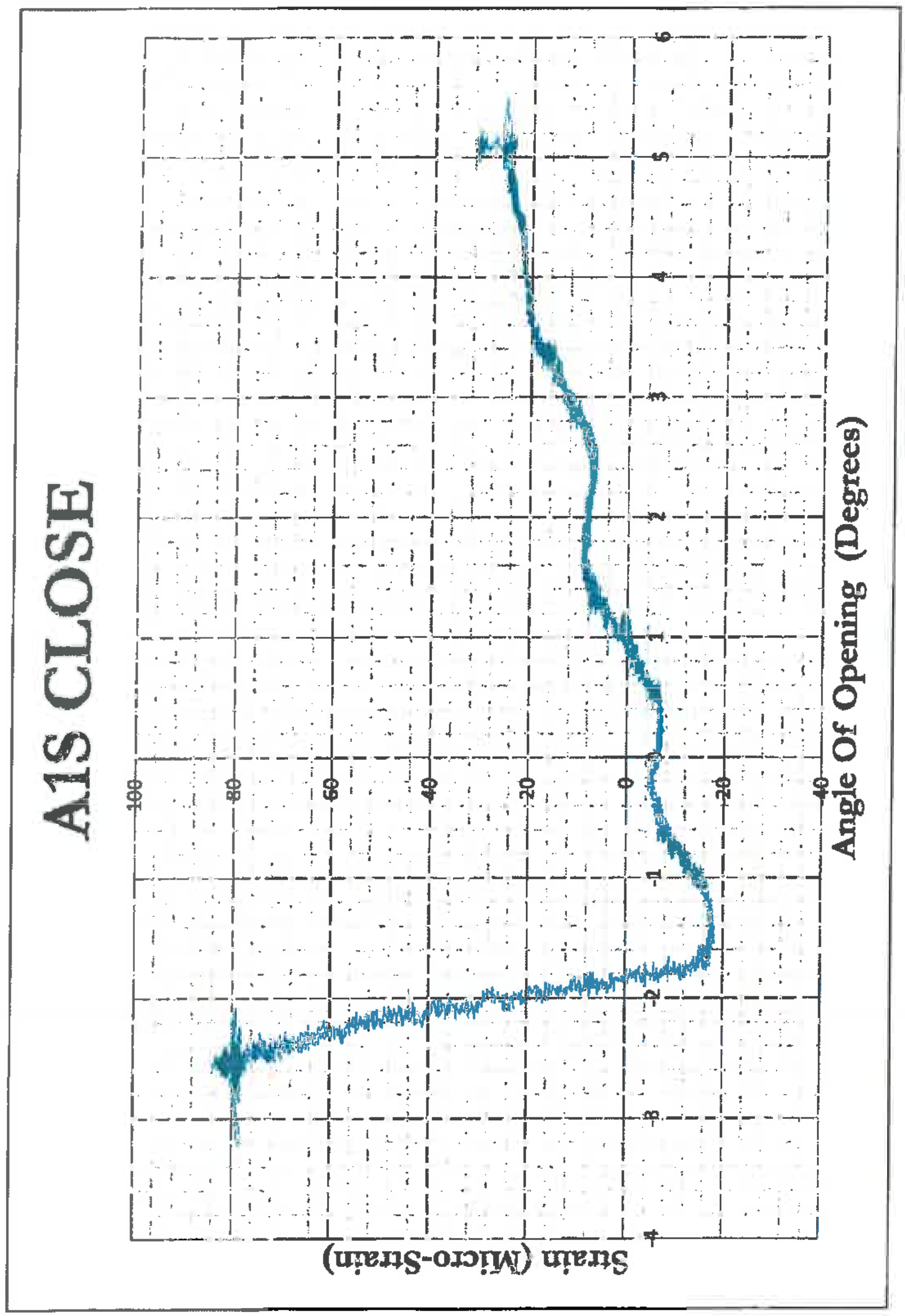
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE



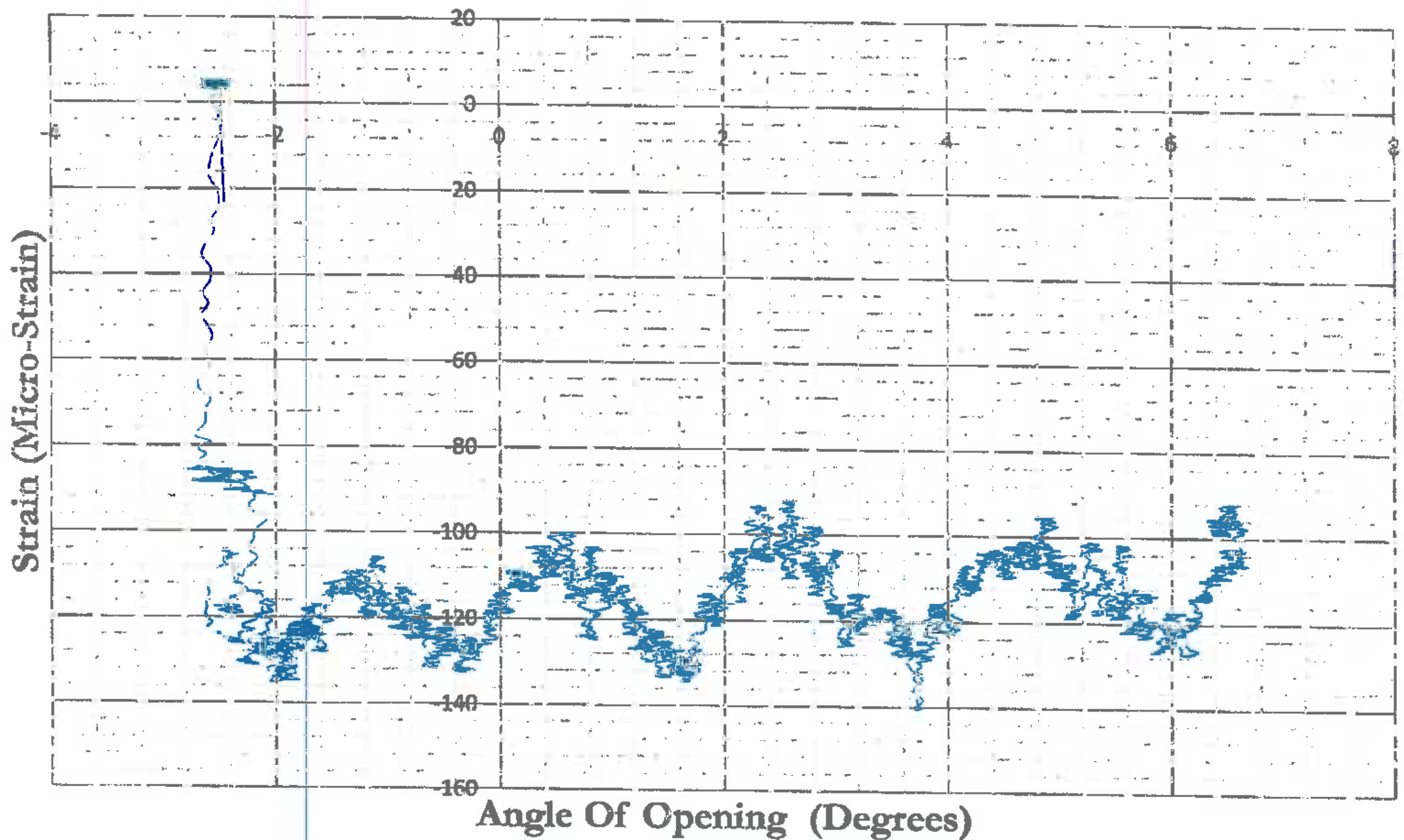
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE



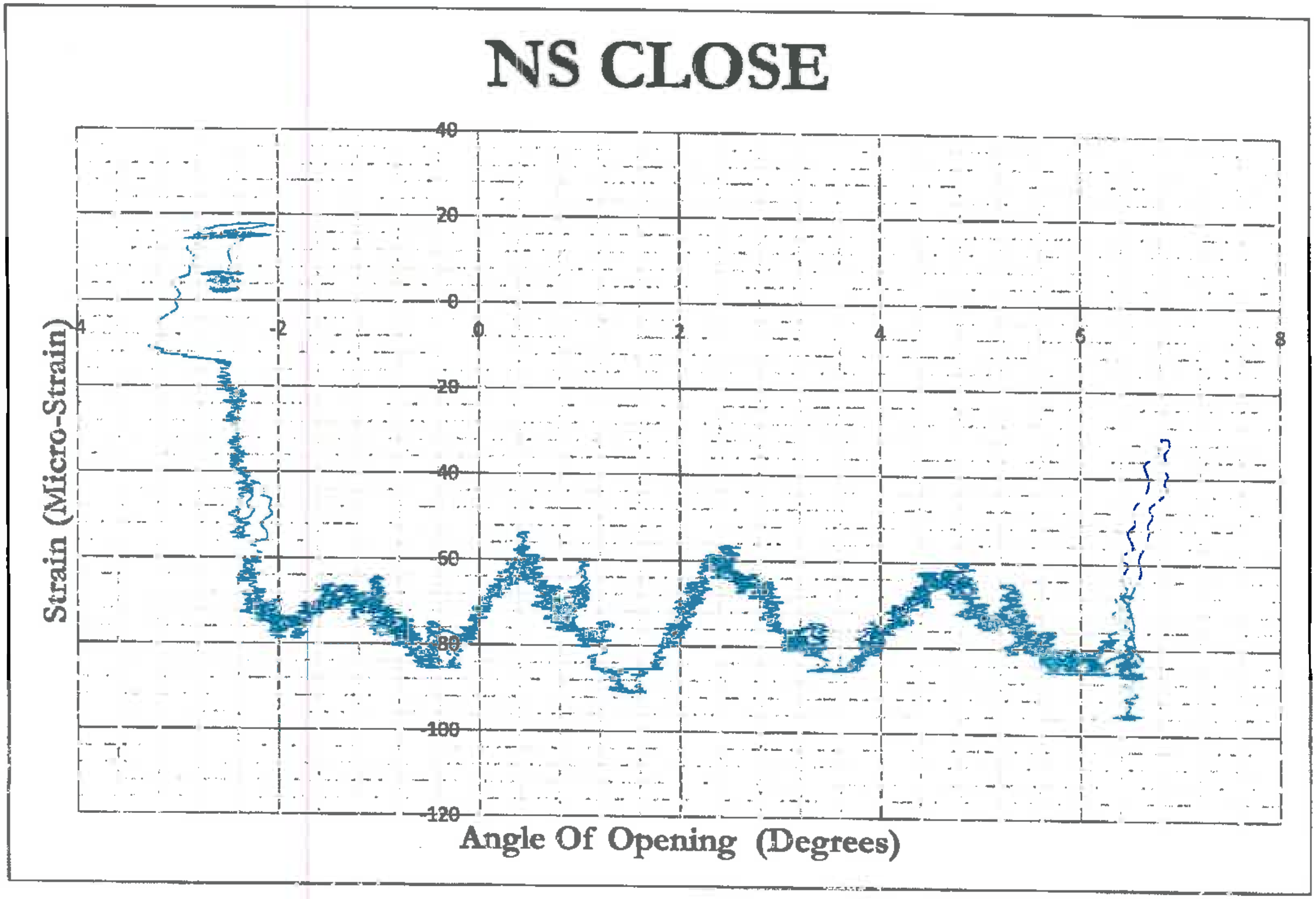
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE



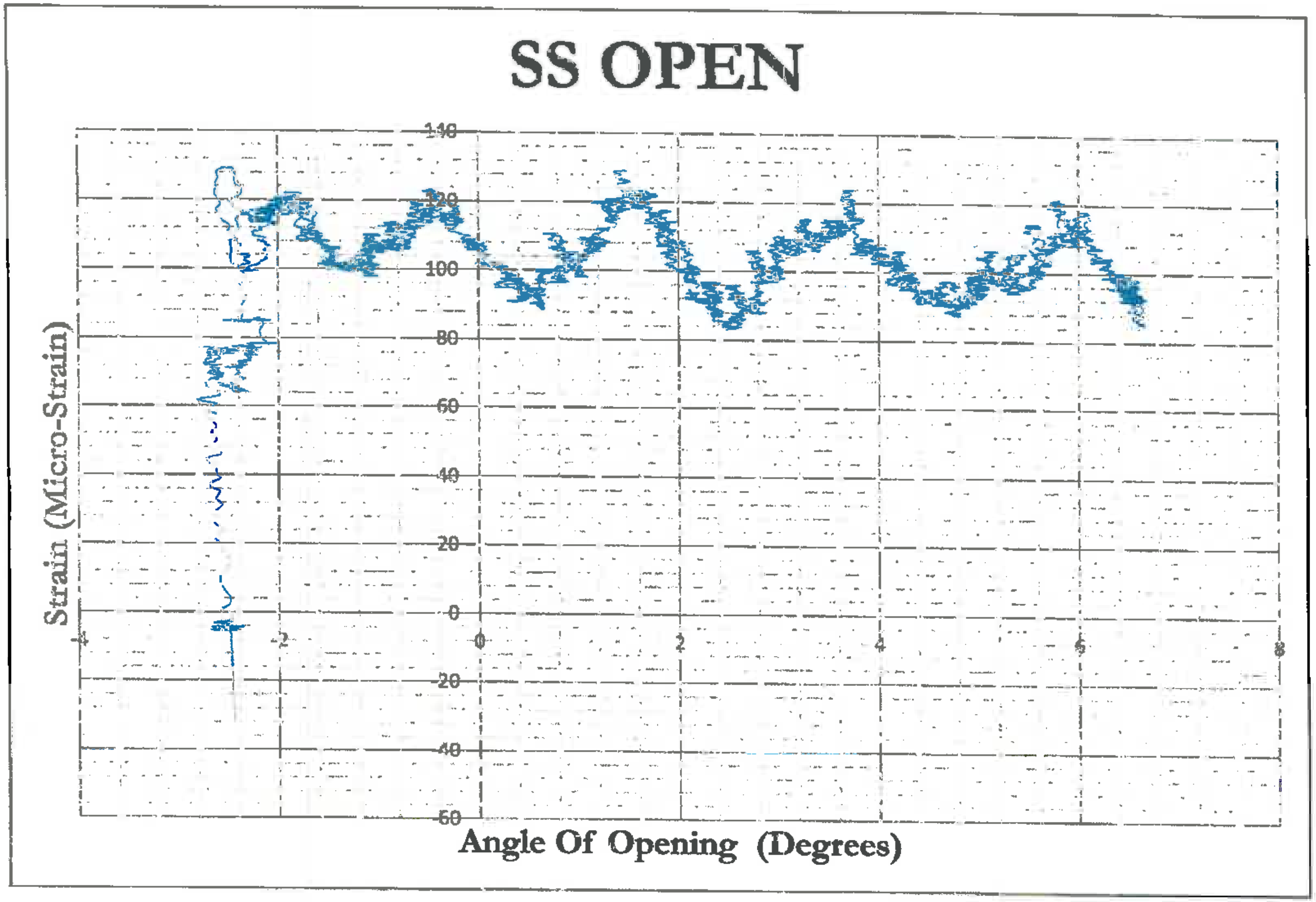
NS OPEN



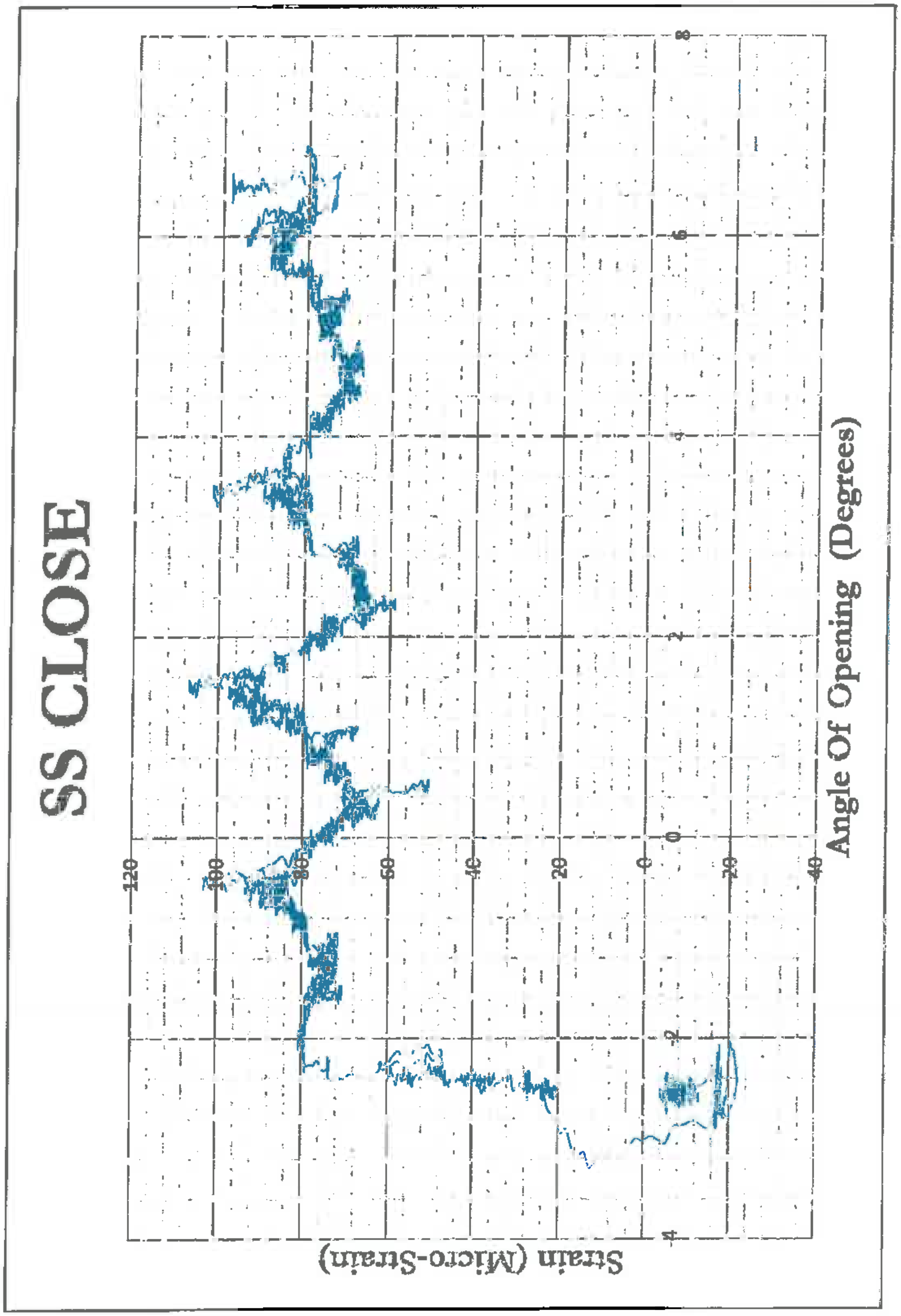
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND16GAUGE



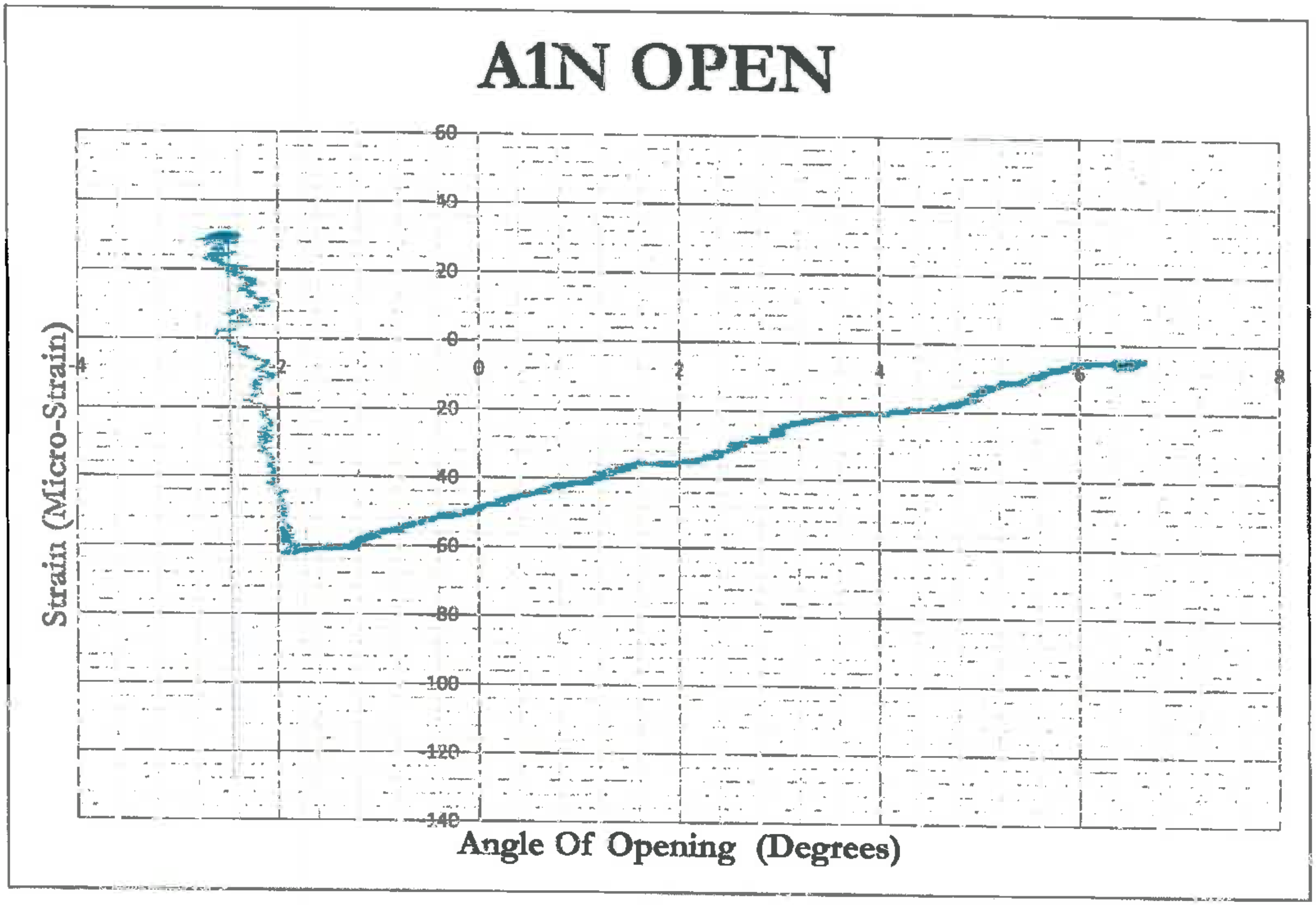
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND16GAUGE



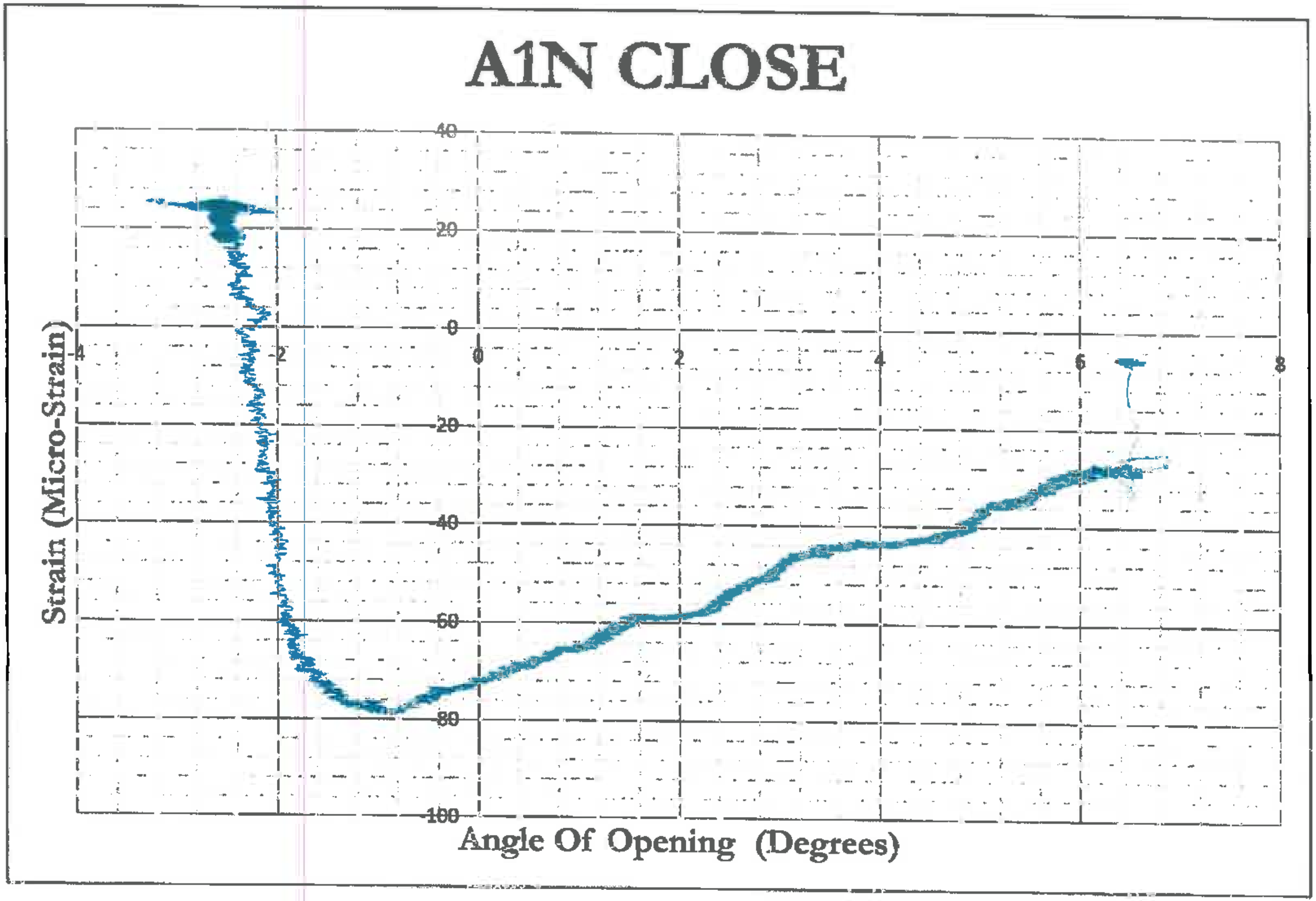
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND16GAUGE



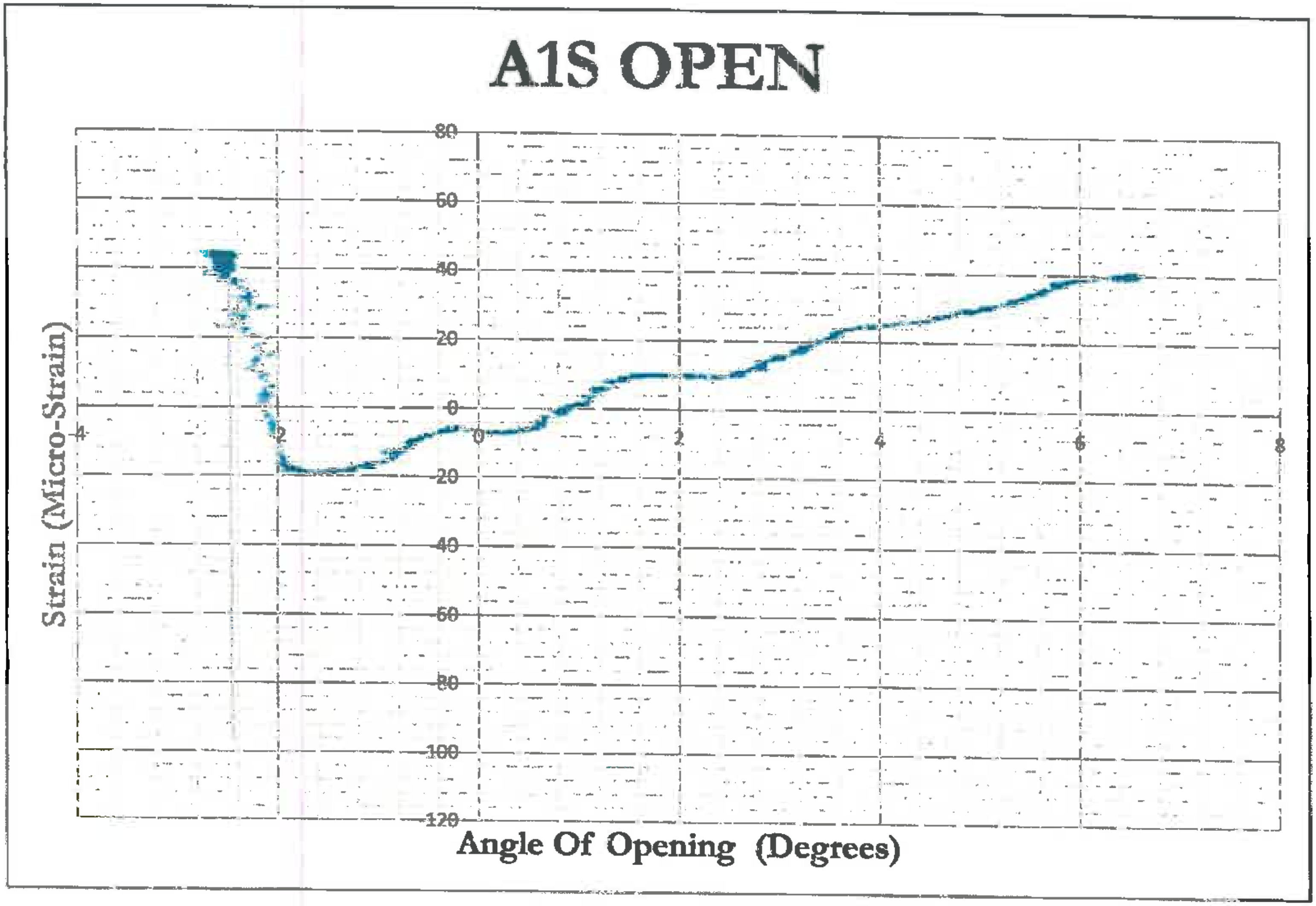
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND16GAUGE



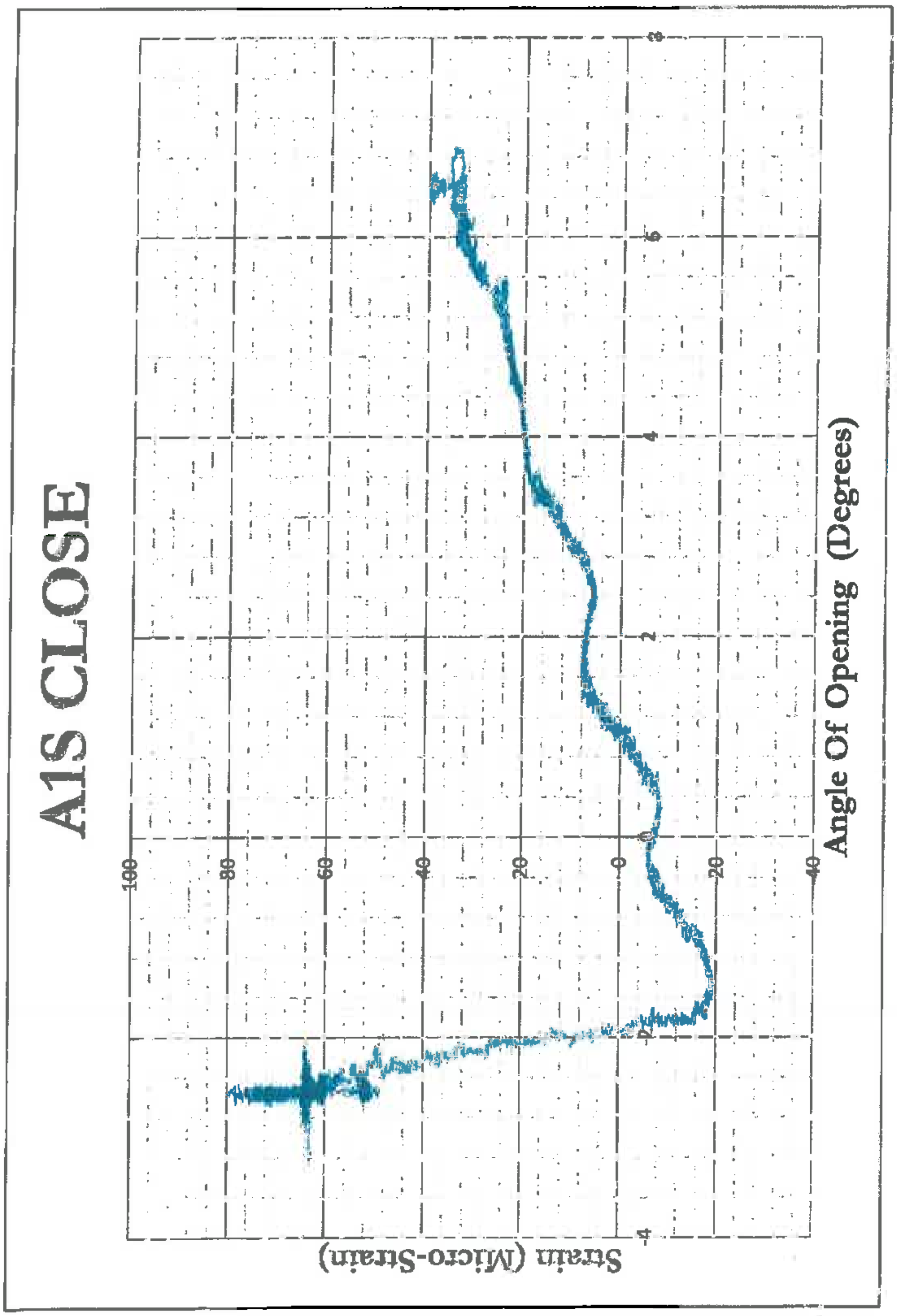
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND16GAUGE



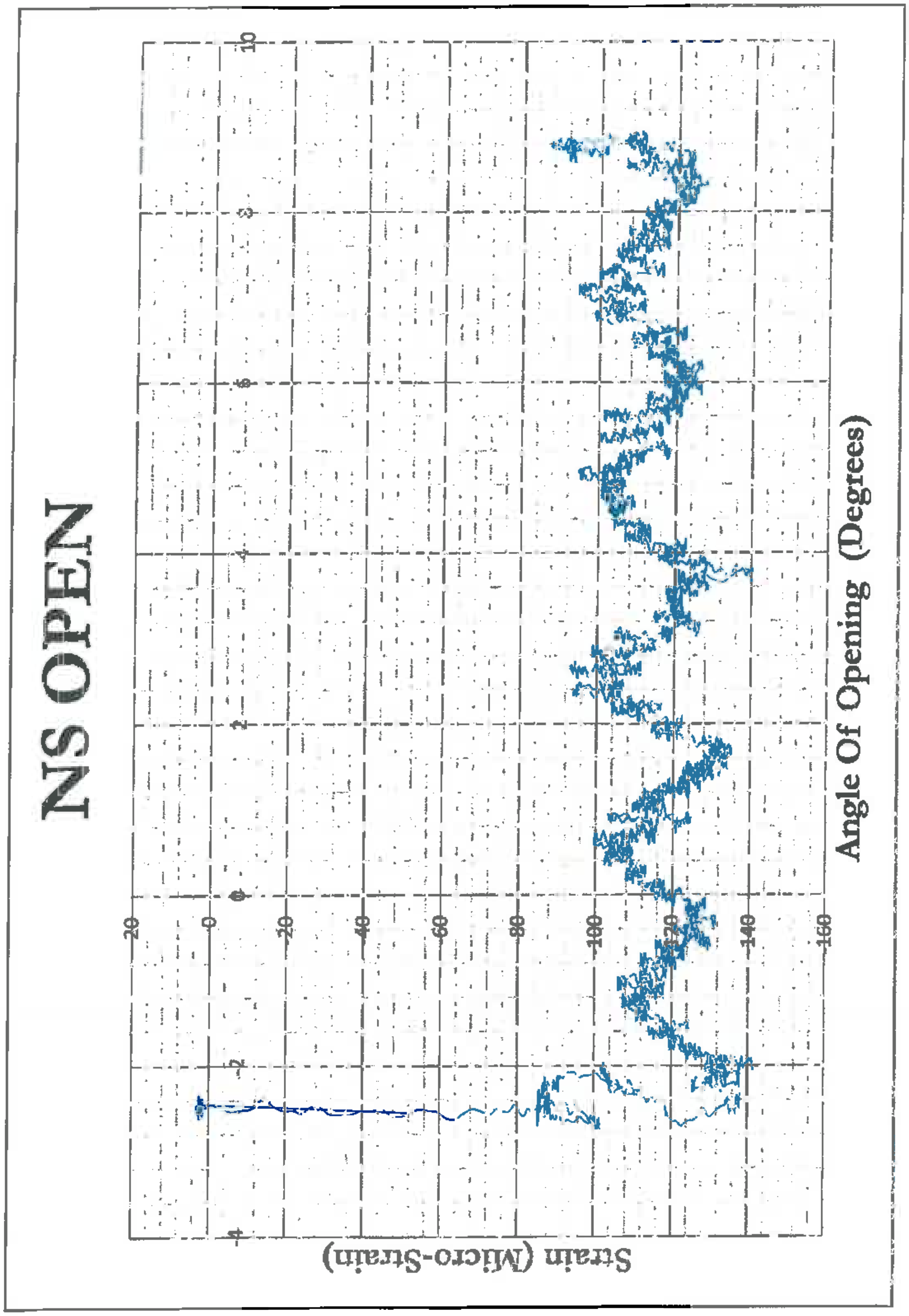
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND16GAUGE



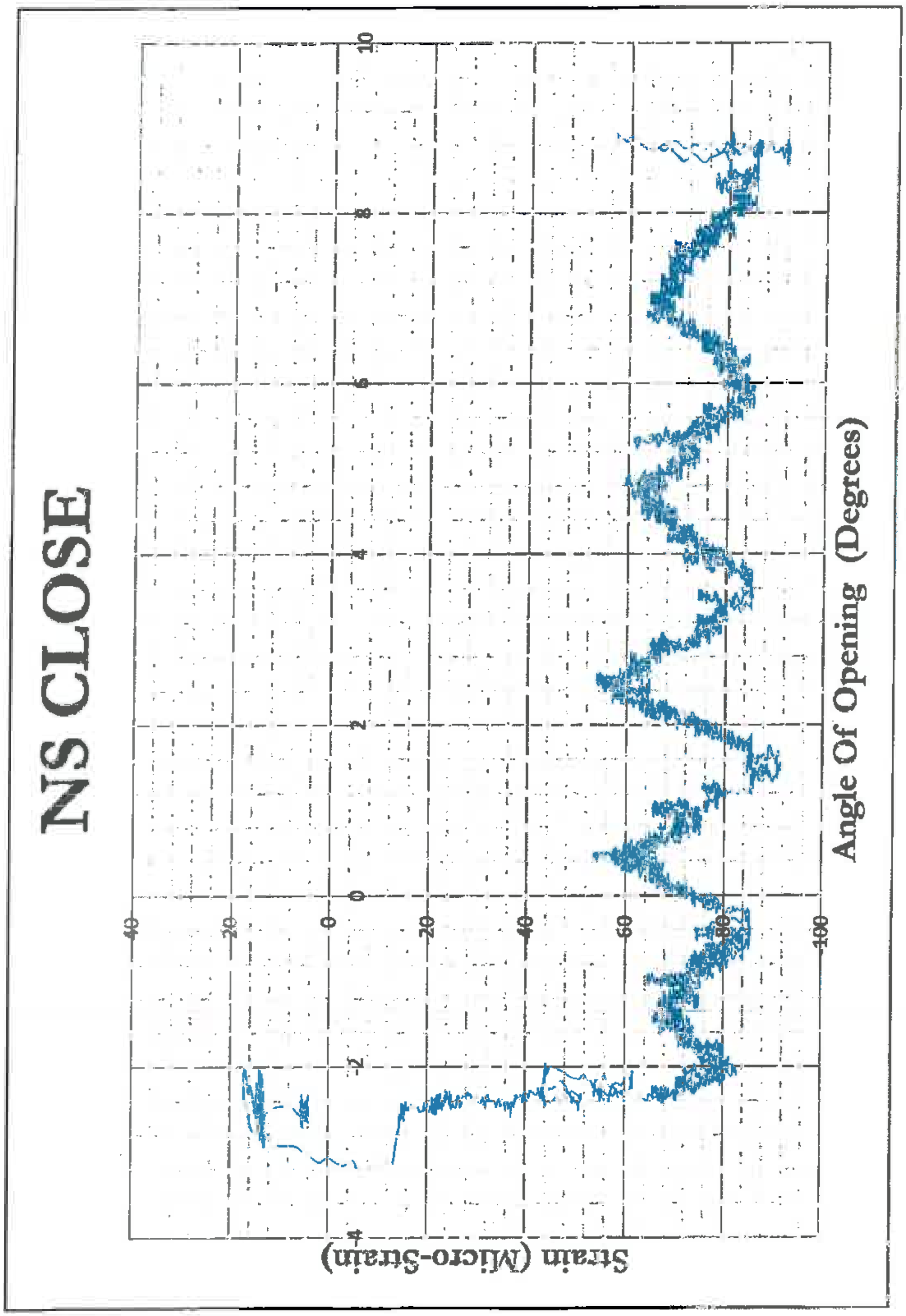
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND16GAUGE



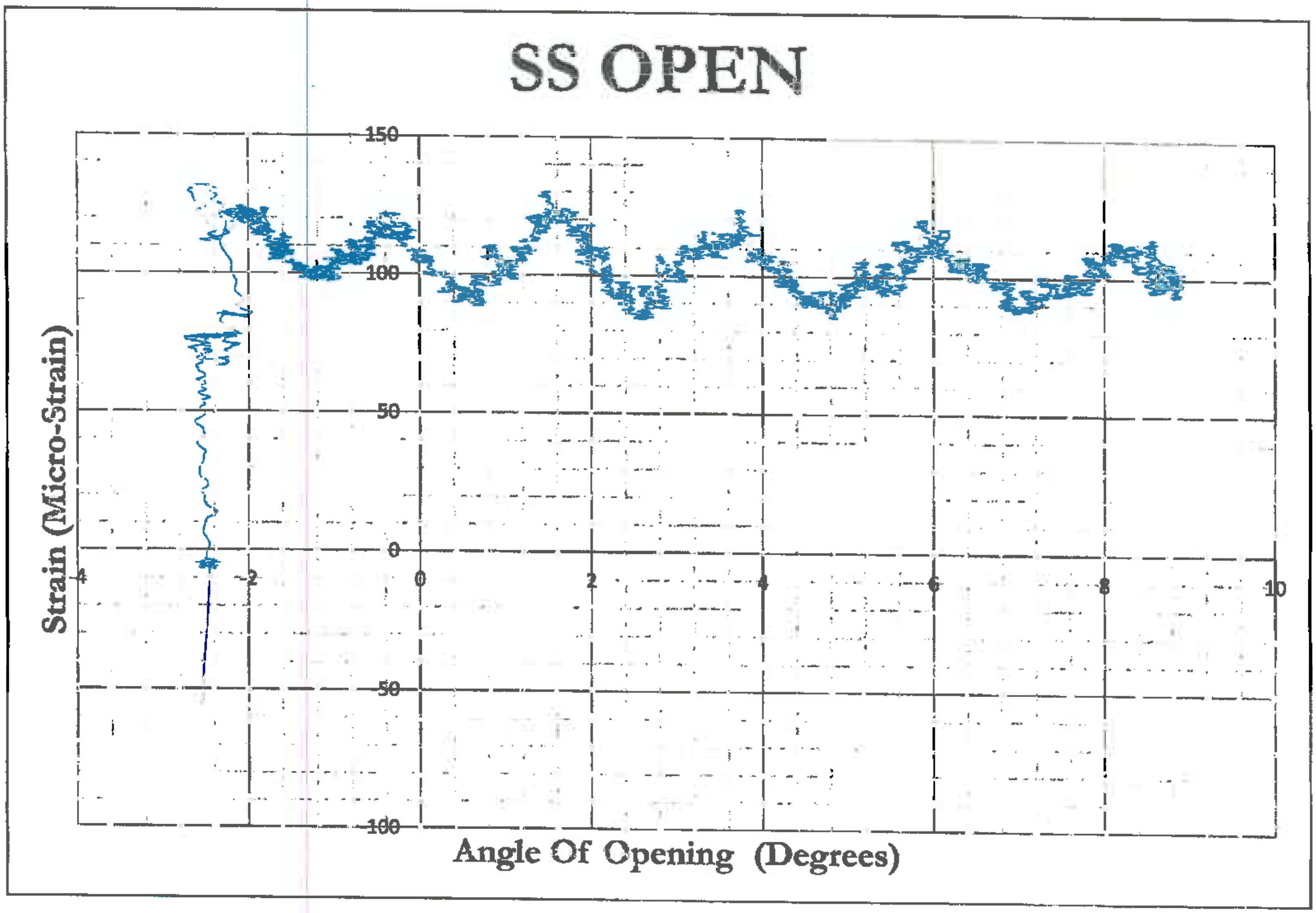
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10GAUGE



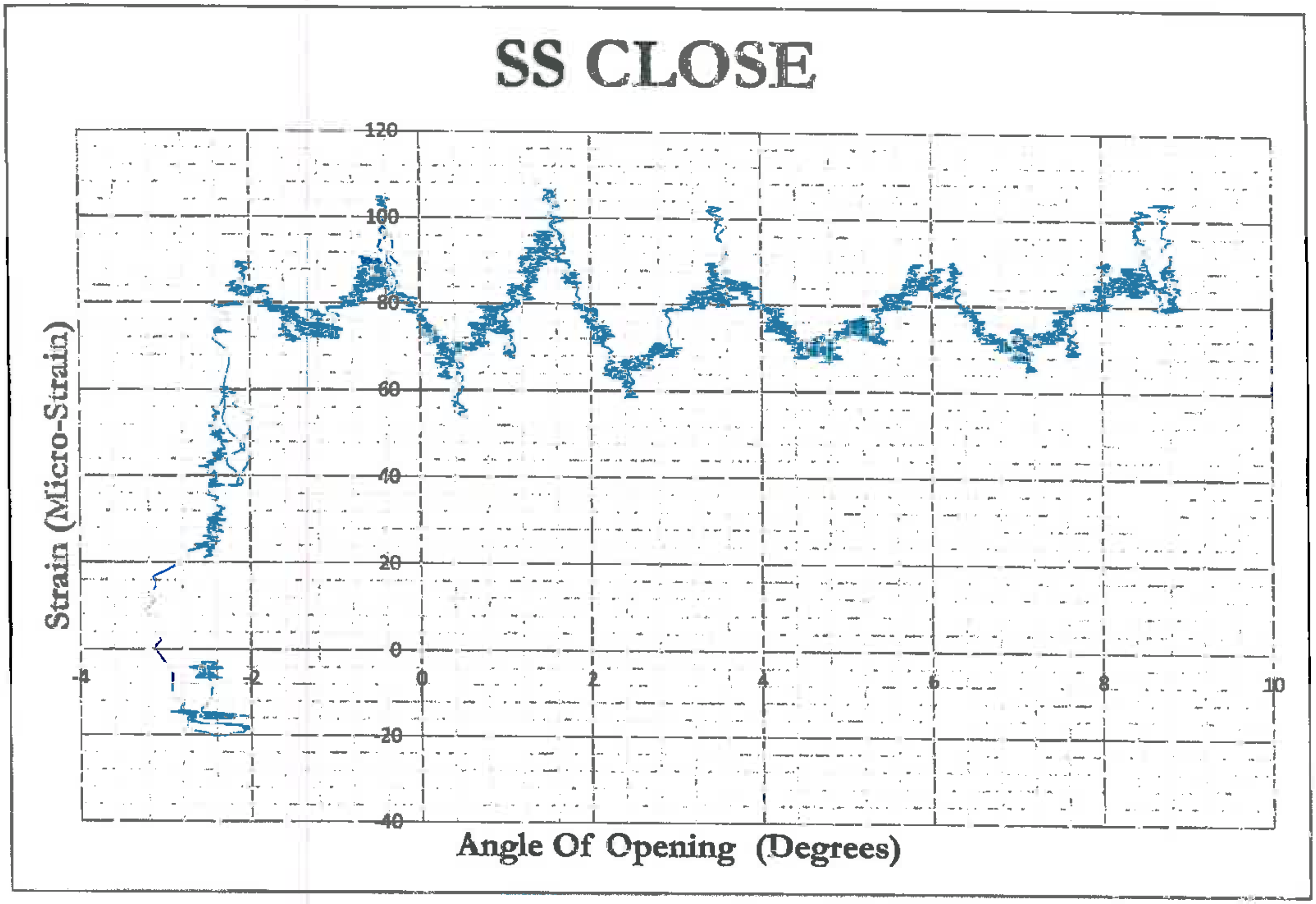
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RAILSHIM10GAUGE



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10GAUGE

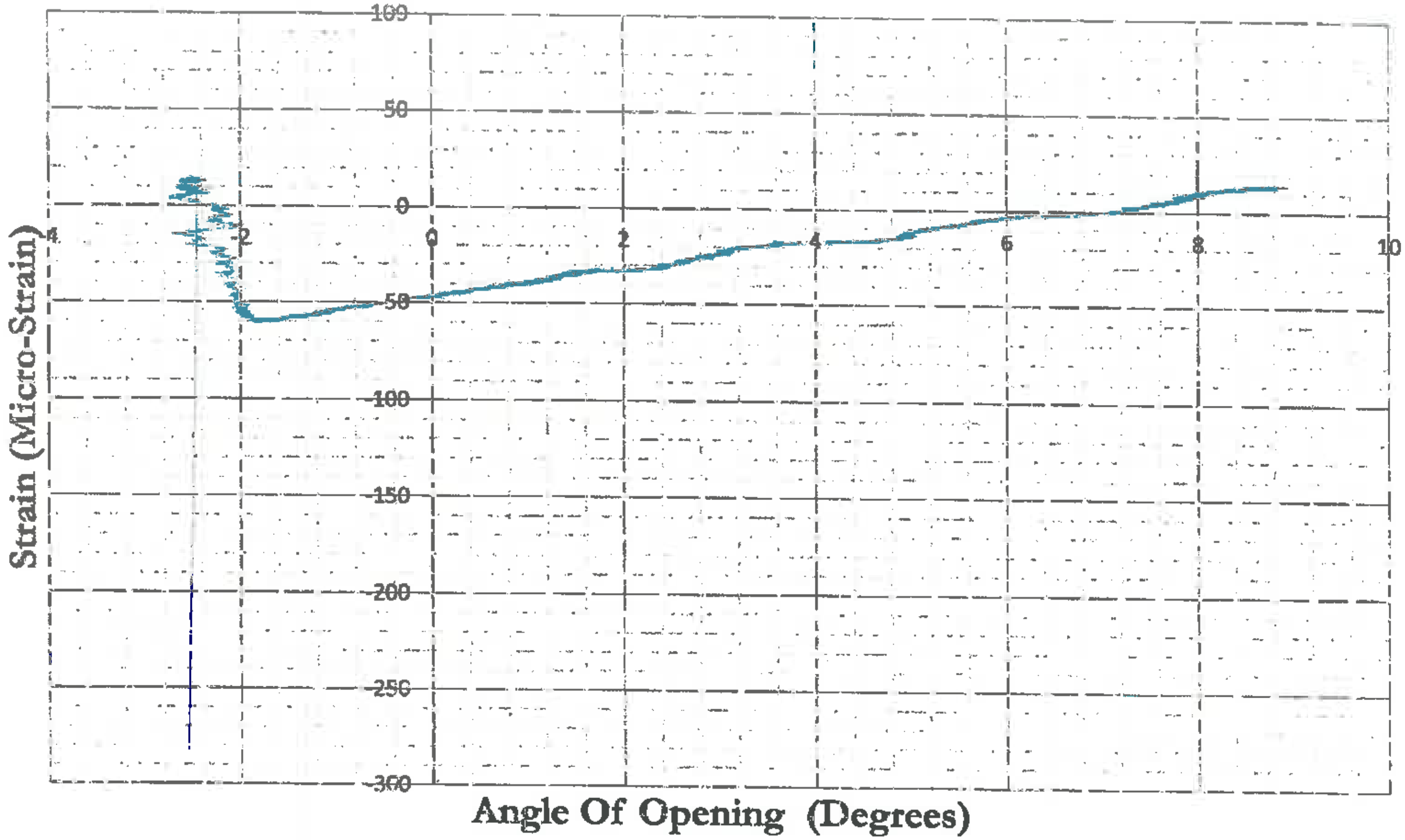


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10GAUGE

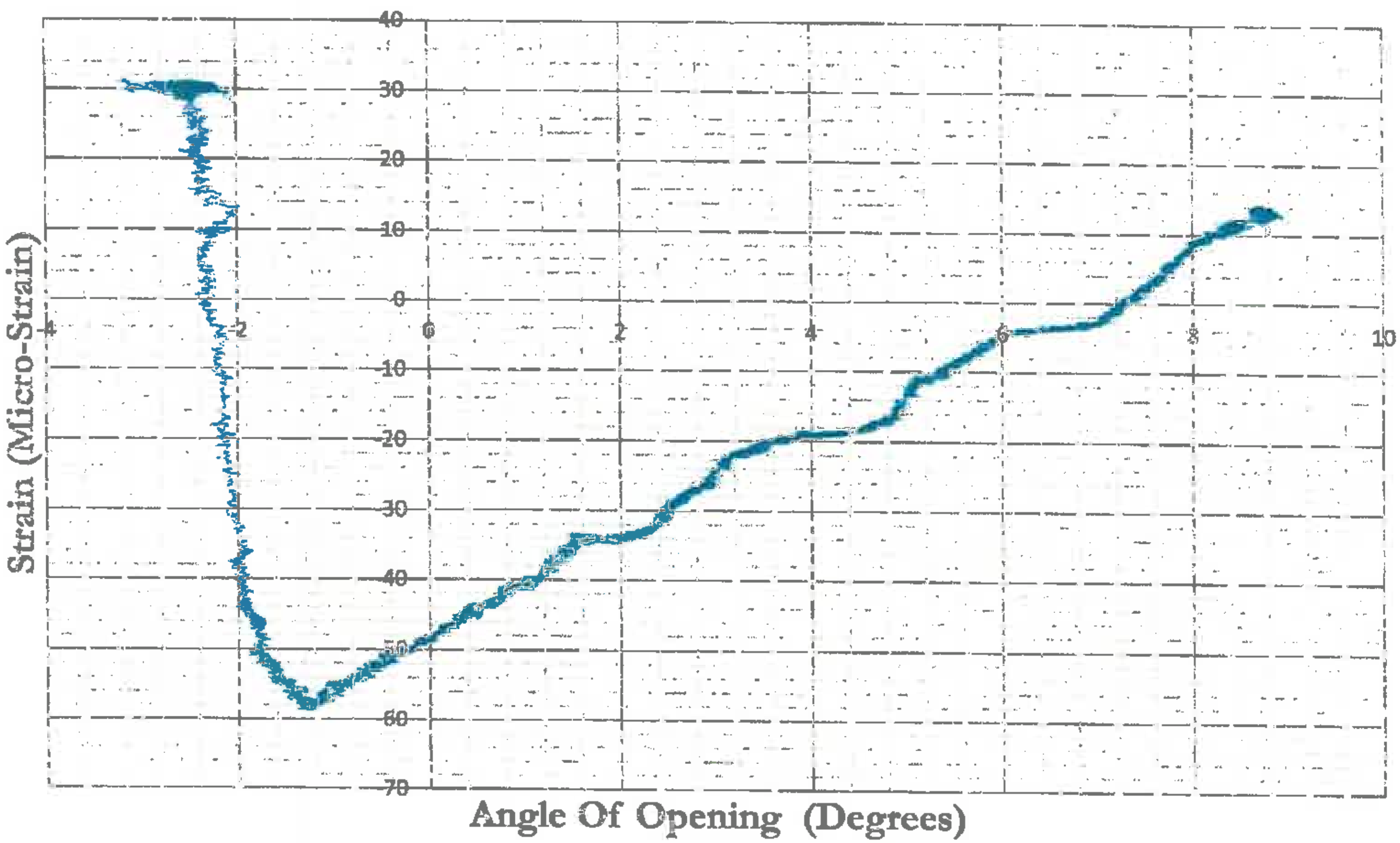


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10GAUGE

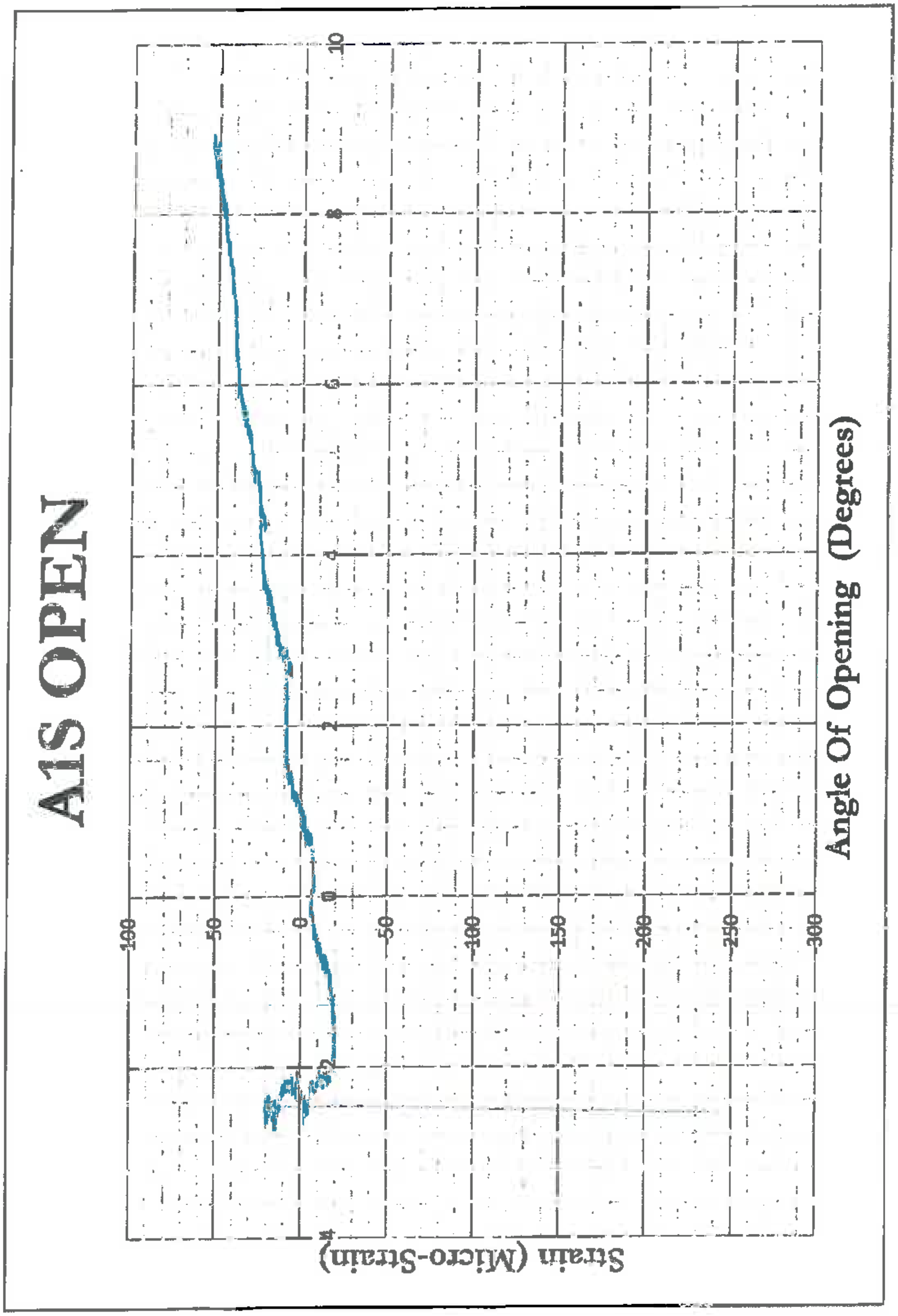
A1N OPEN



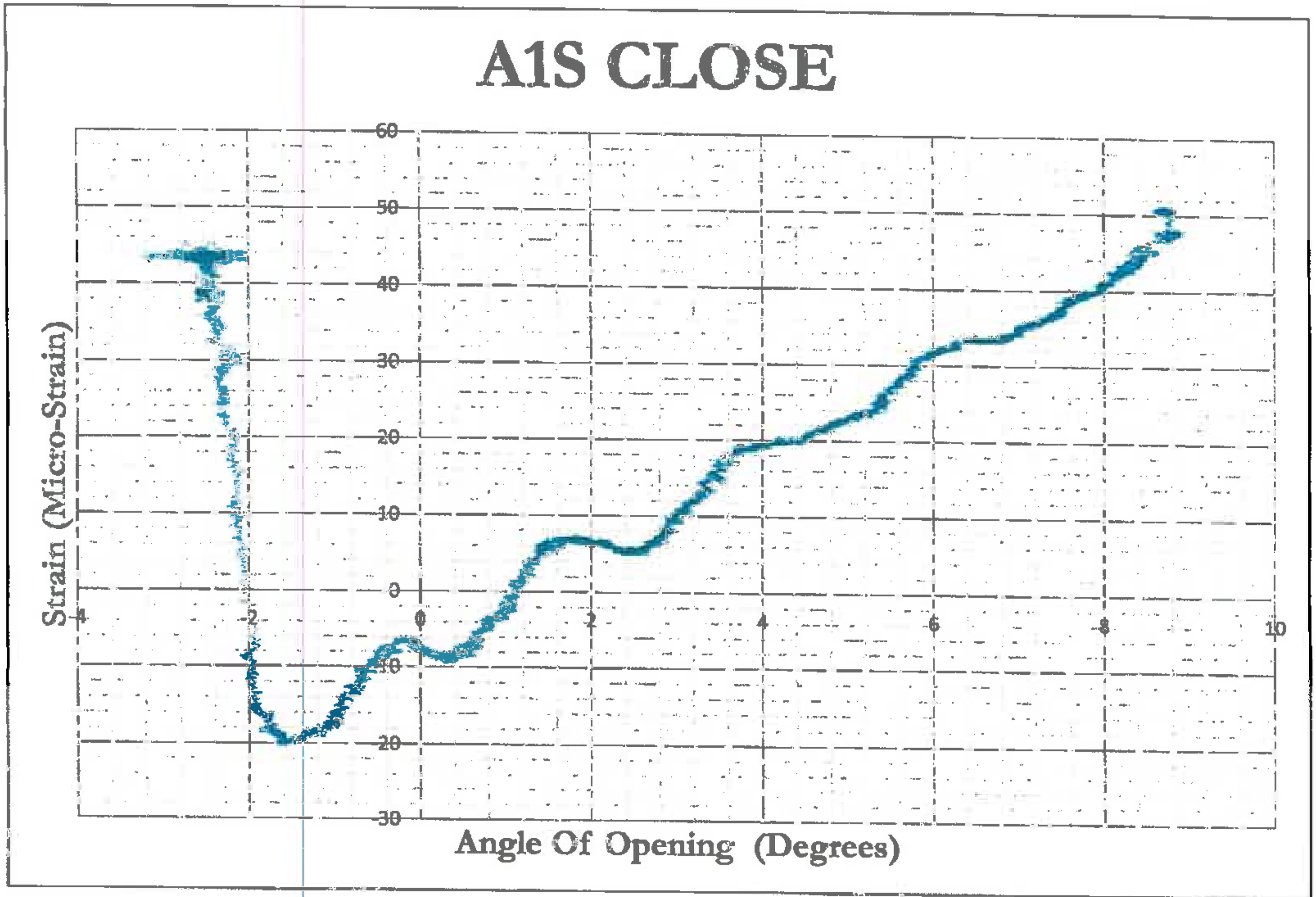
A1N CLOSE


40
30
20
10
0
10
20
30
40
50
60
70
-4
-2
0
2
4
6
8
10
Strain (Micro-Strain)
Angle Of Opening (Degrees)

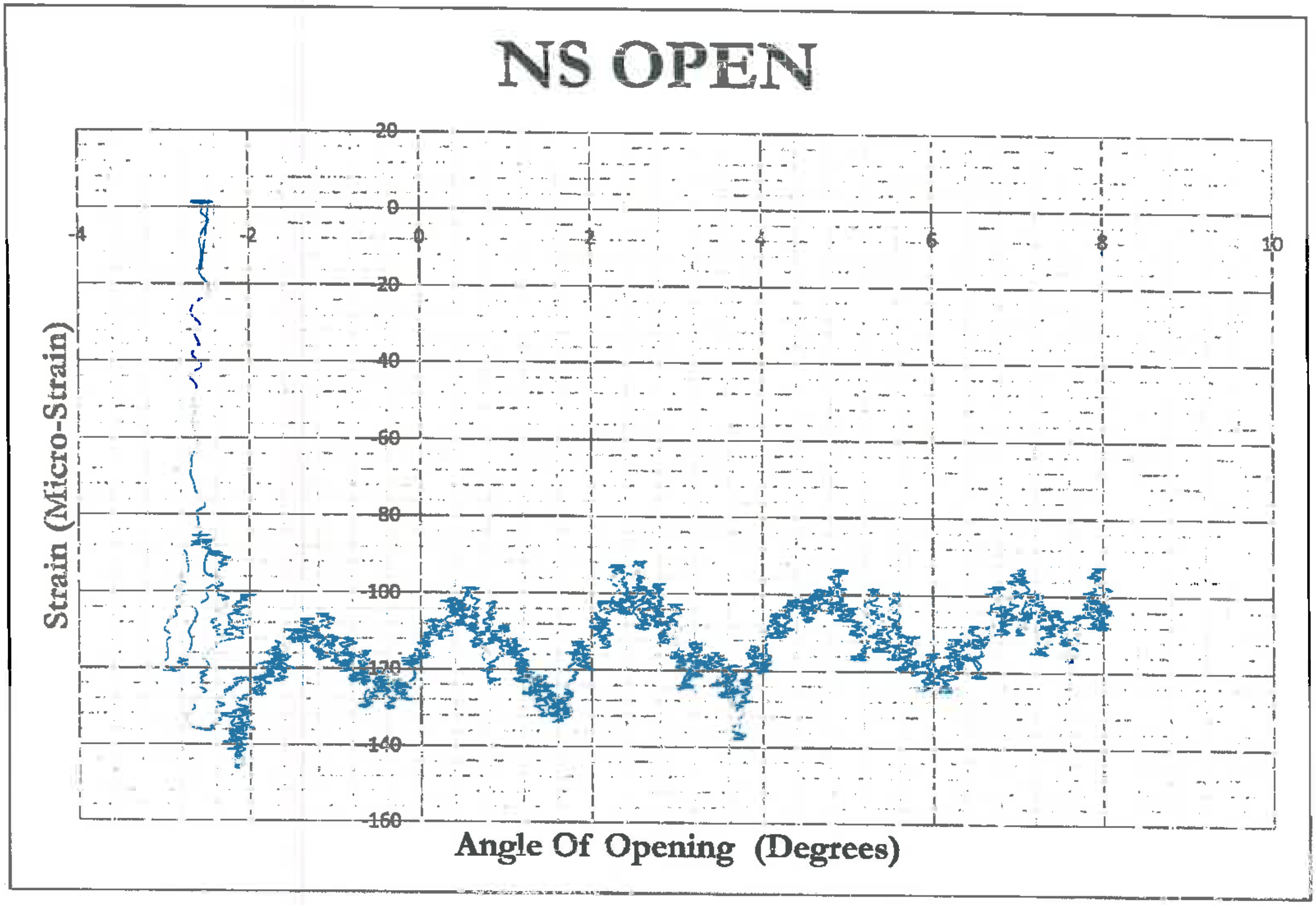
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10GAUGE



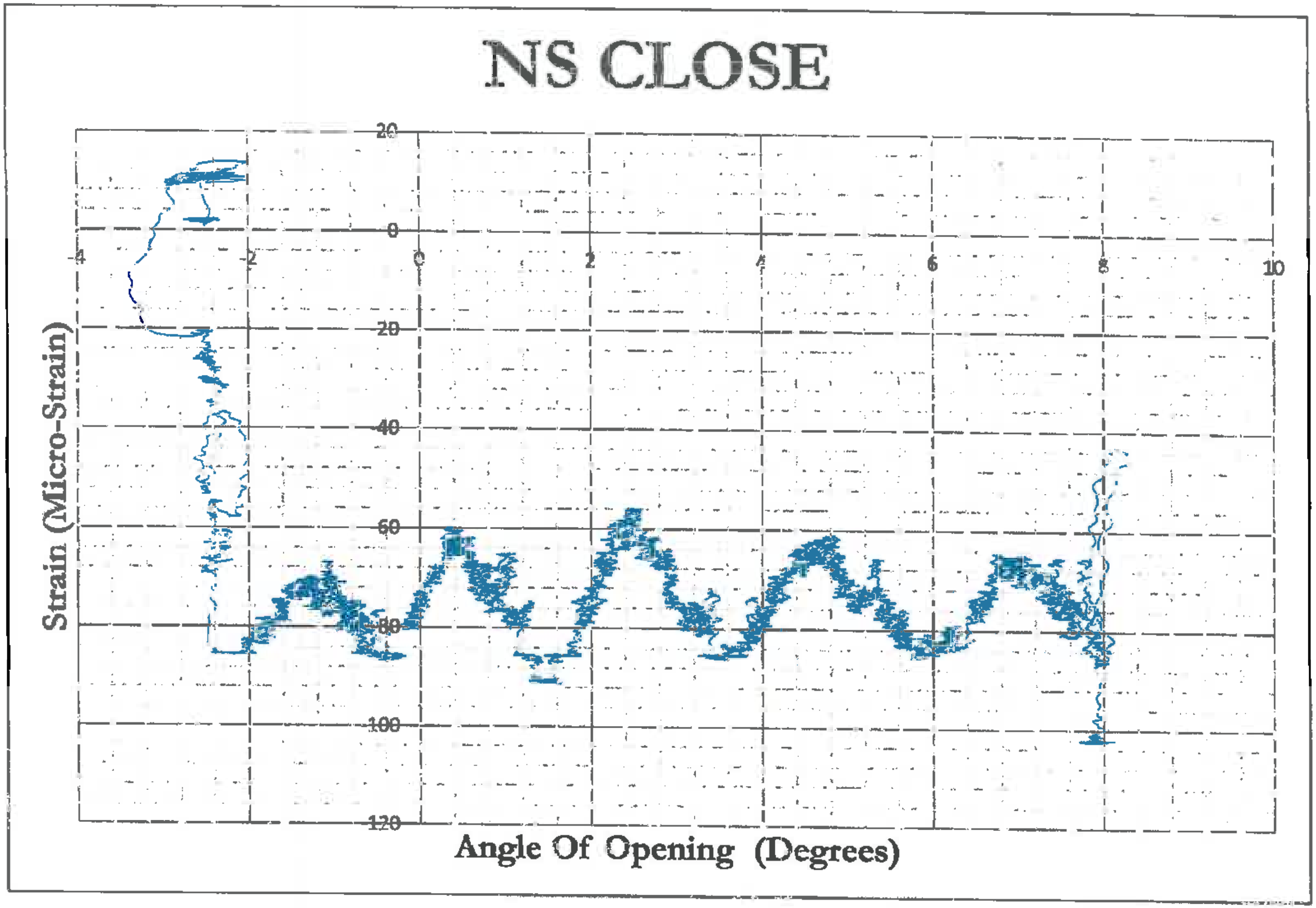
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10GAUGE



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM16GAUGE

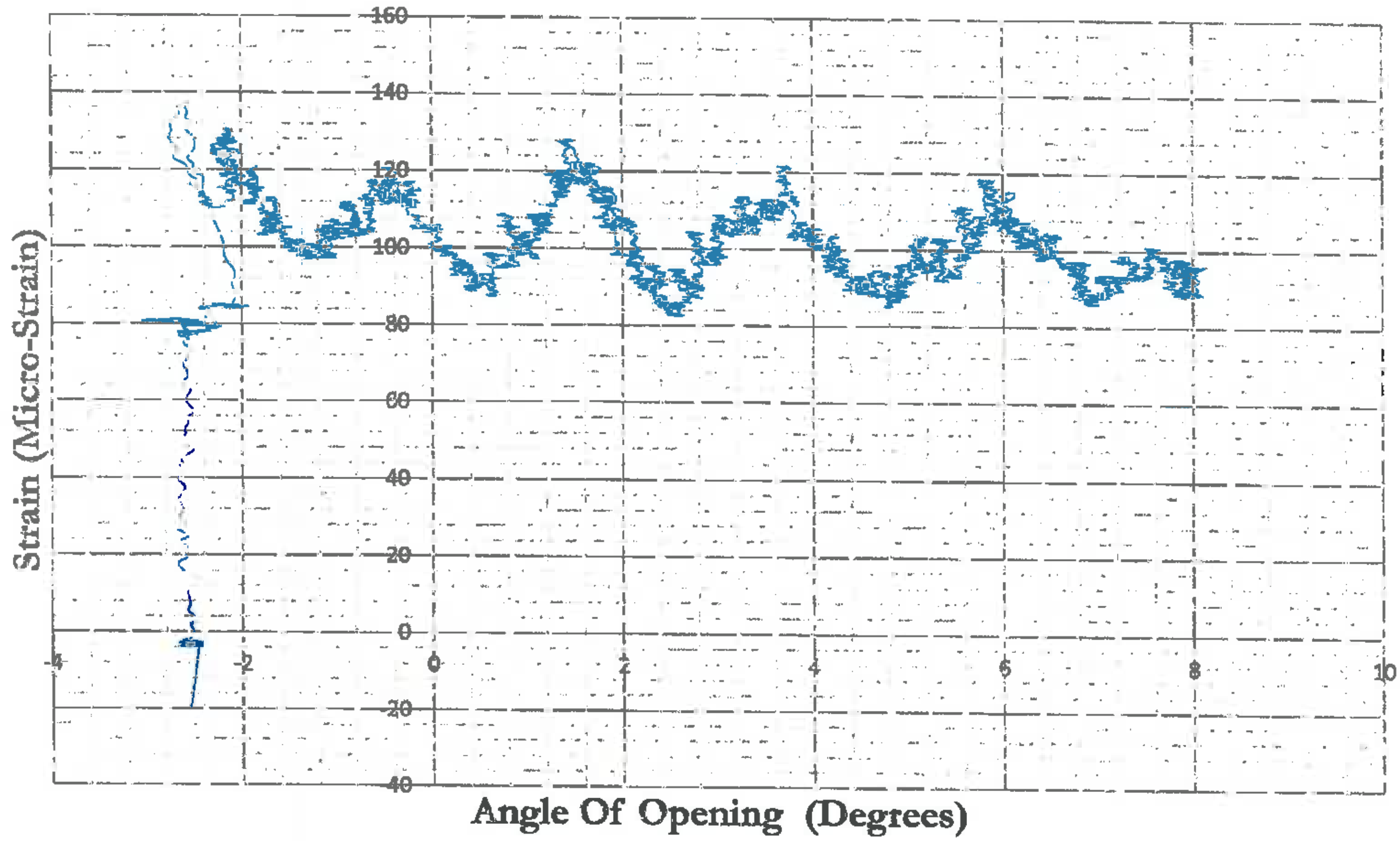


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM16GAUGE

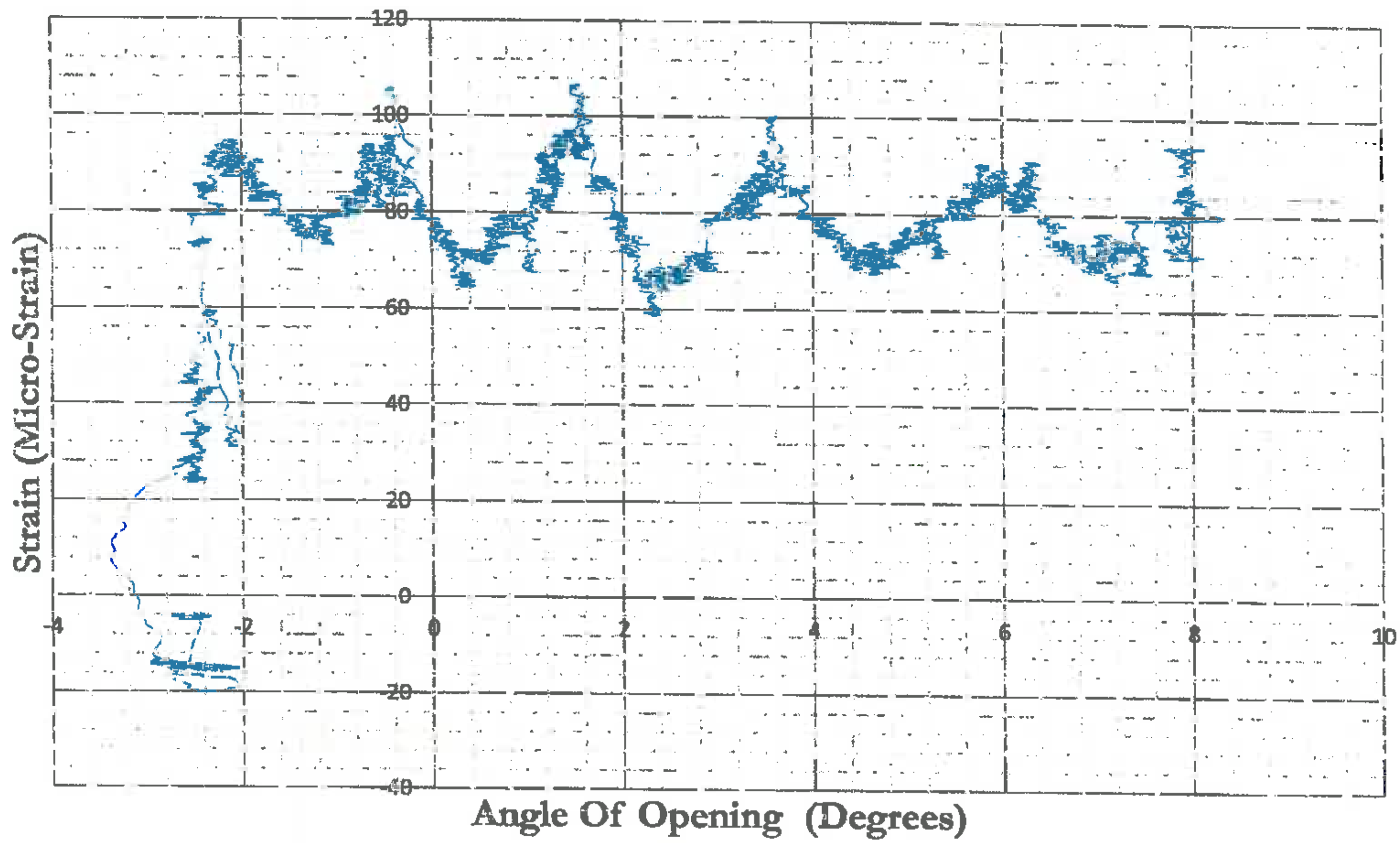


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM16GAUGE

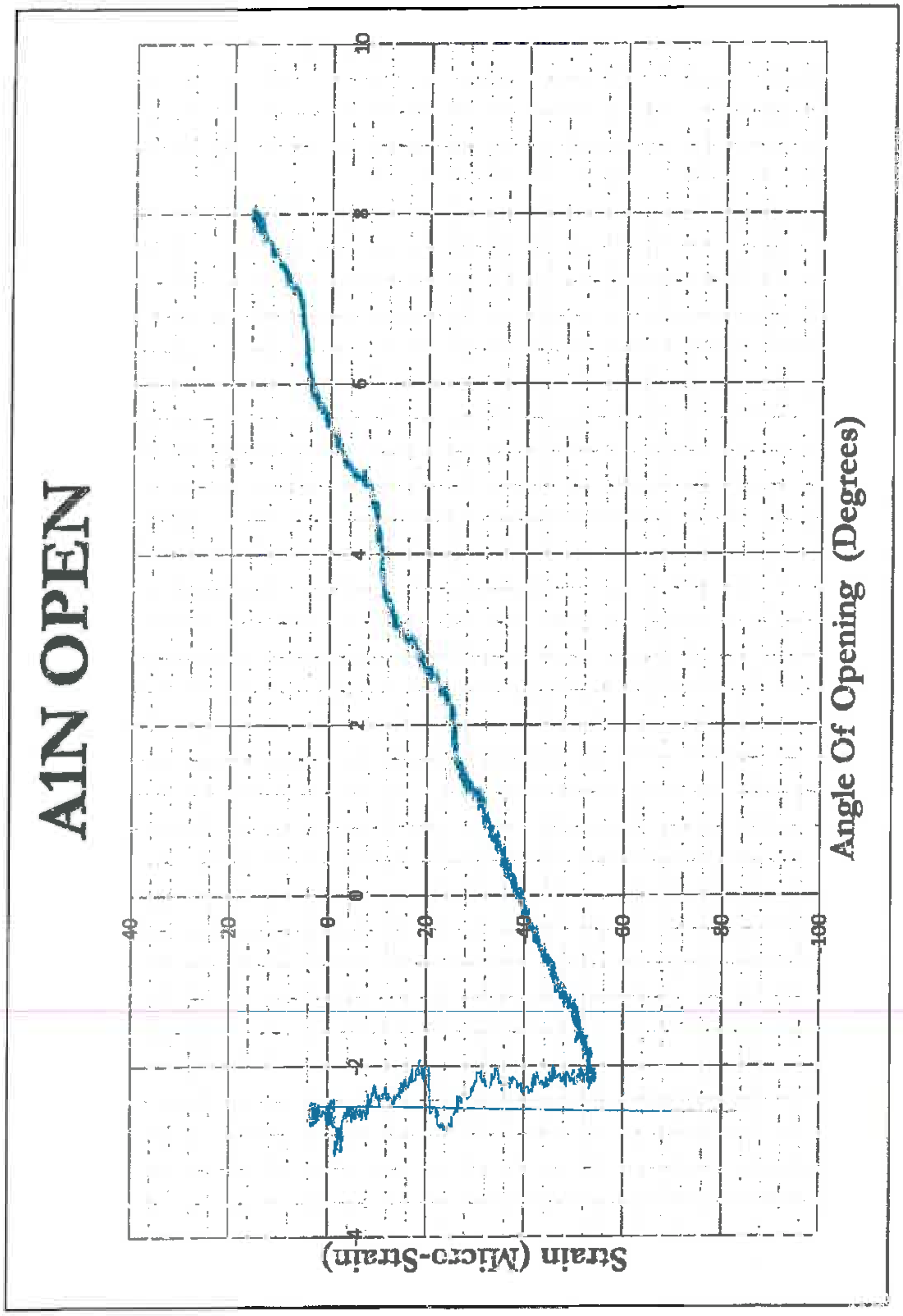
SS OPEN



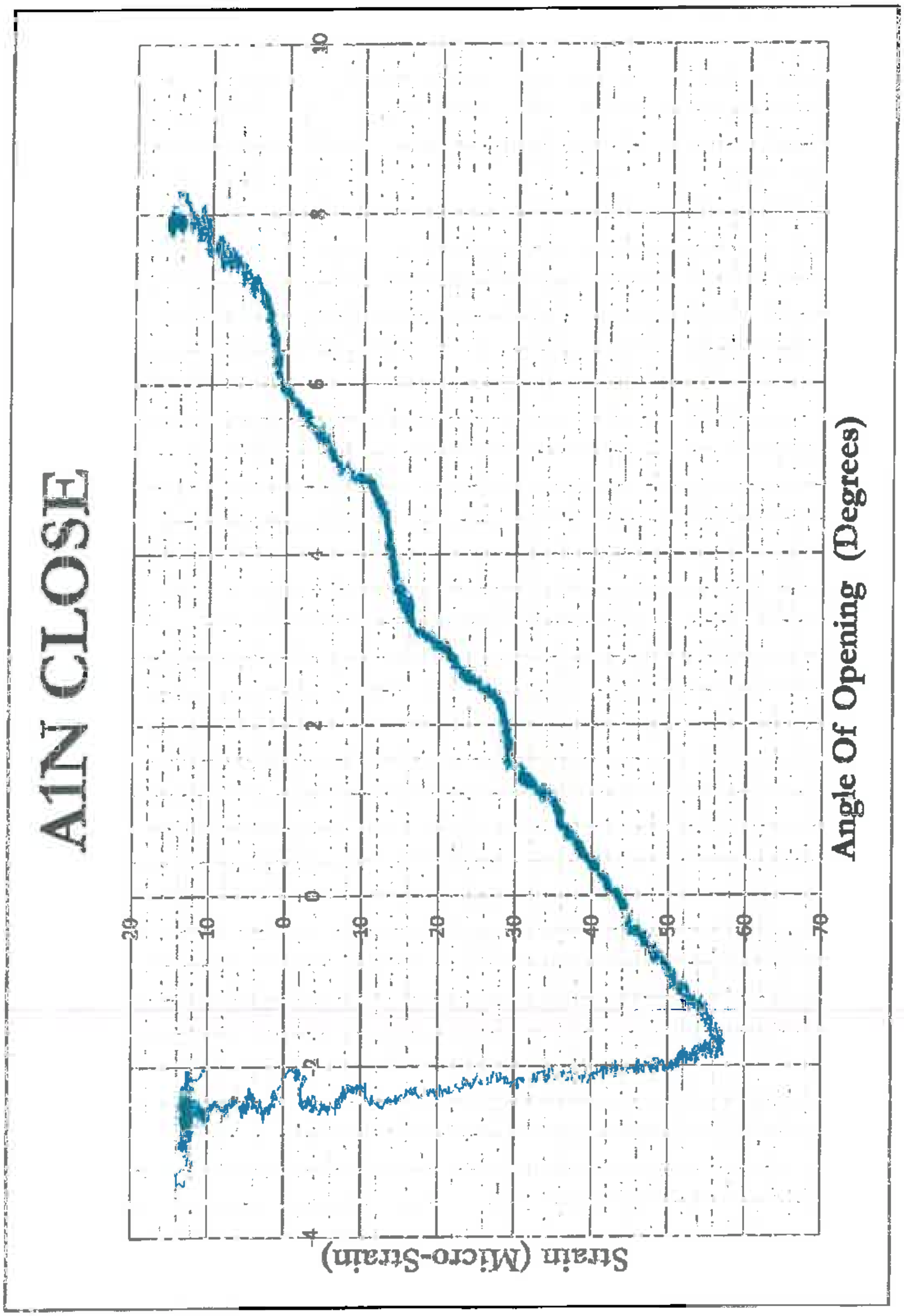
SS CLOSE


120
100
80
60
40
20
0
-20
-40
-4
-2
0
2
4
6
8
10
Strain (Micro-Strain)
Angle Of Opening (Degrees)

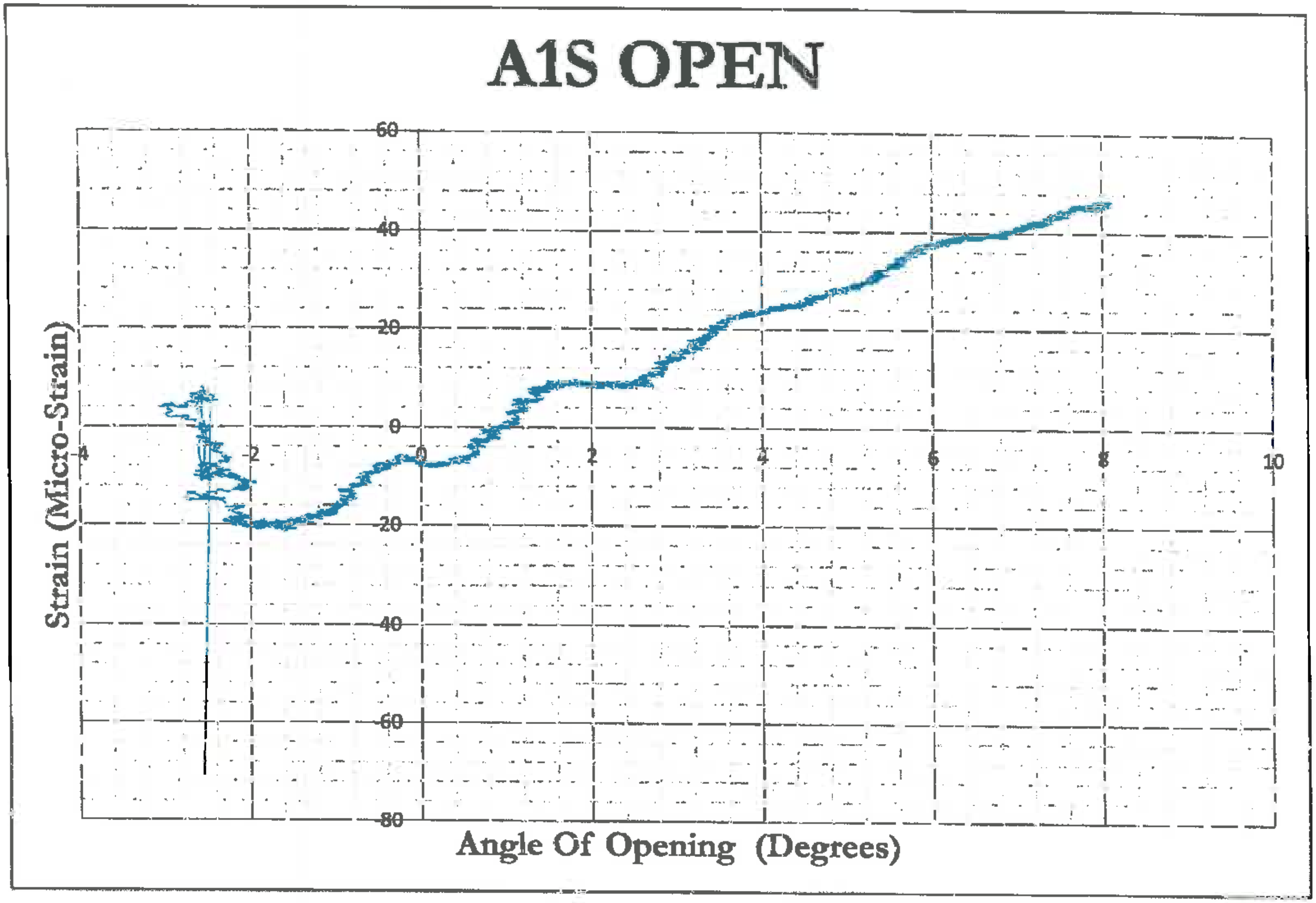
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM16GAUGE



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM16GAUGE

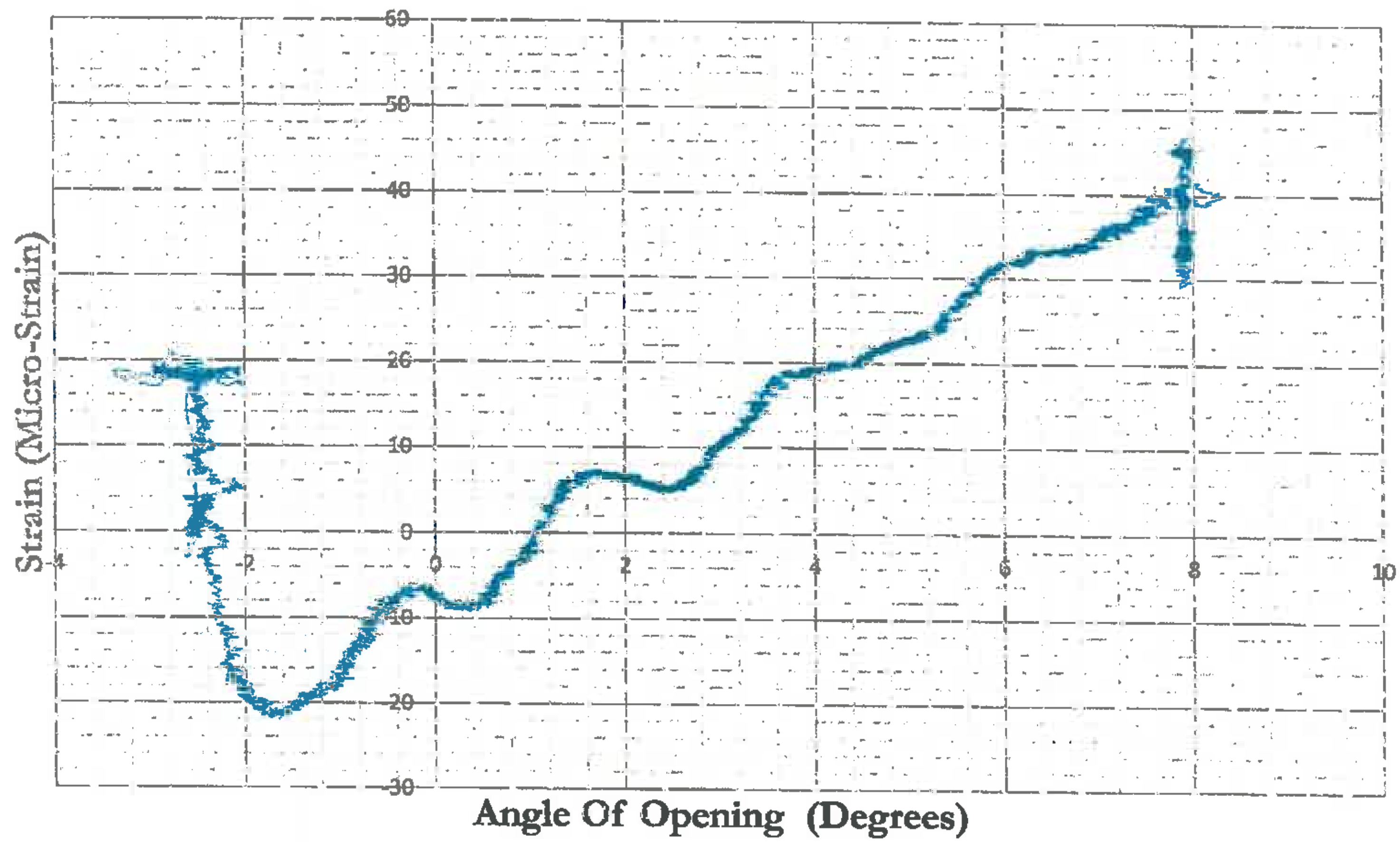


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM16GAUGE

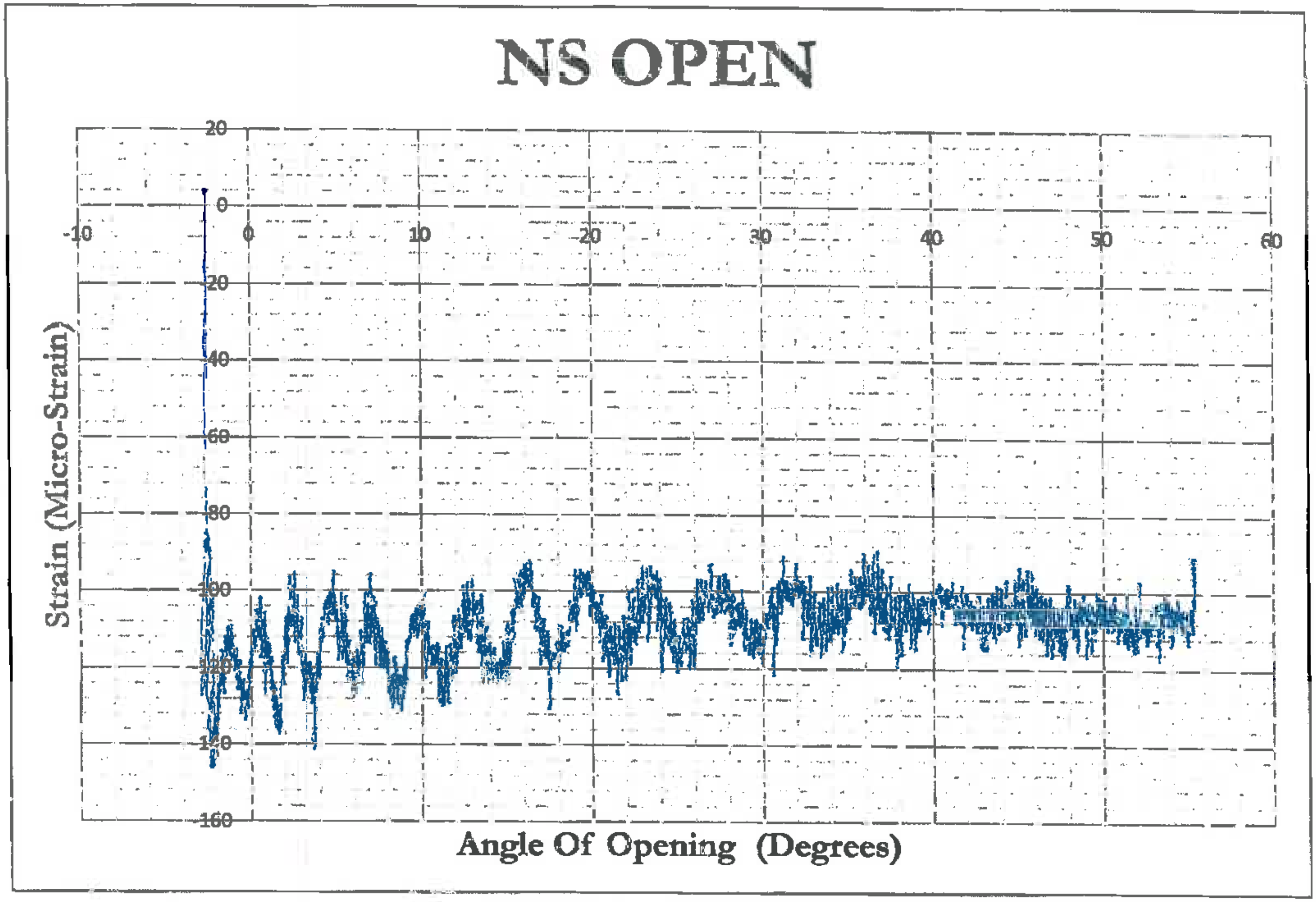


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM16GAUGE

A1S CLOSE

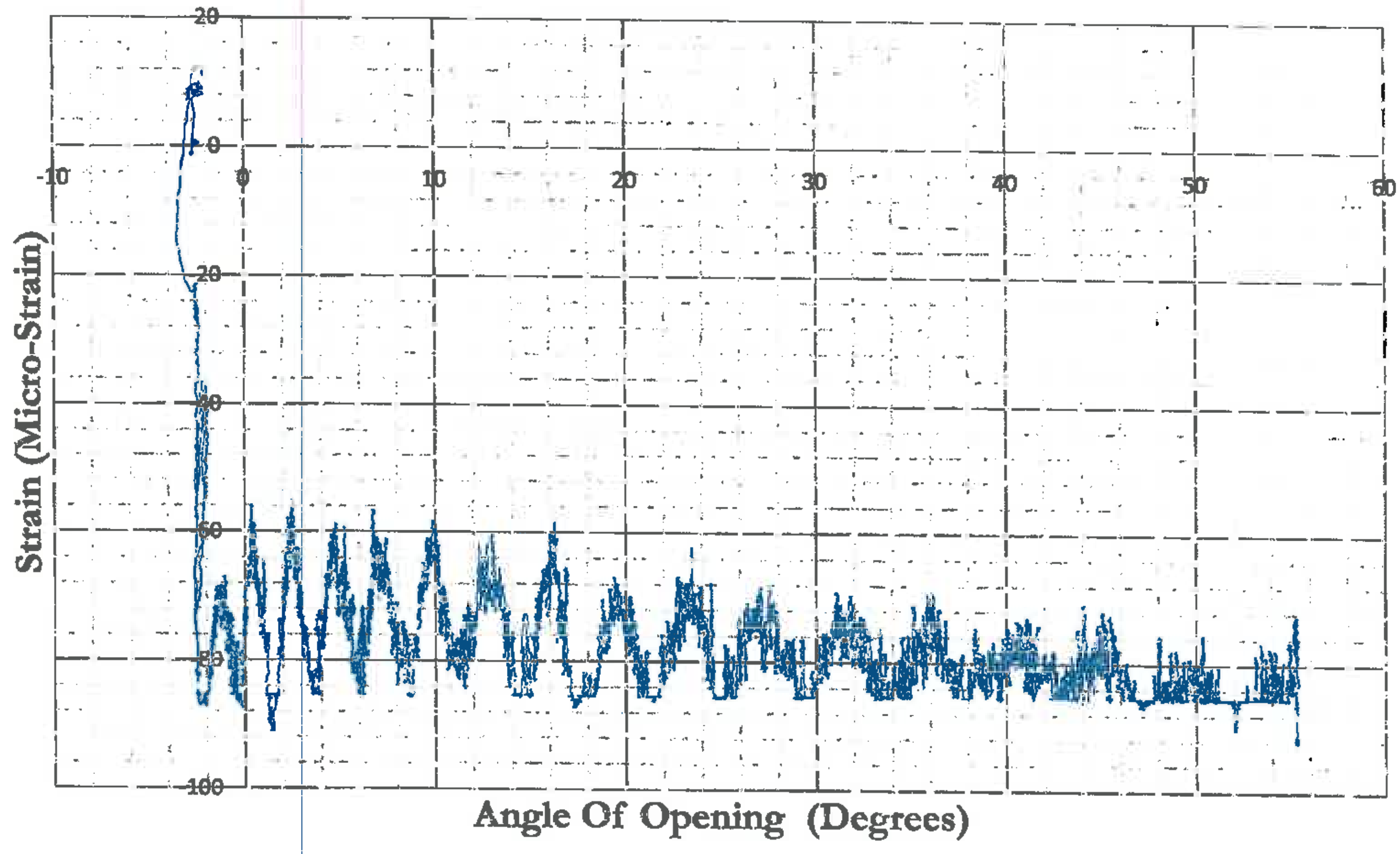


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE
SHIMSOUTFULLOPEN1

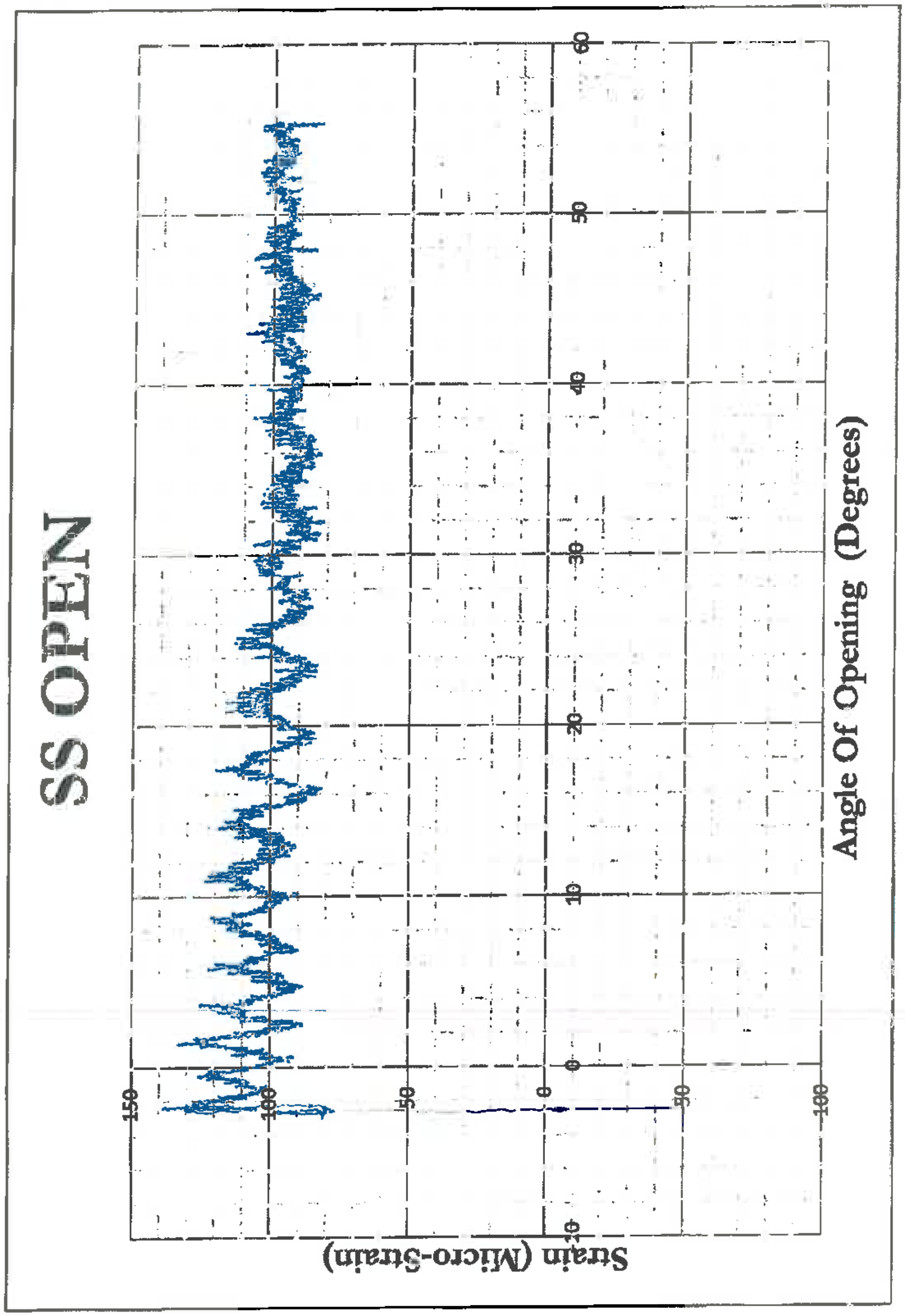


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE
SHIMSOUTFULLOPEN1

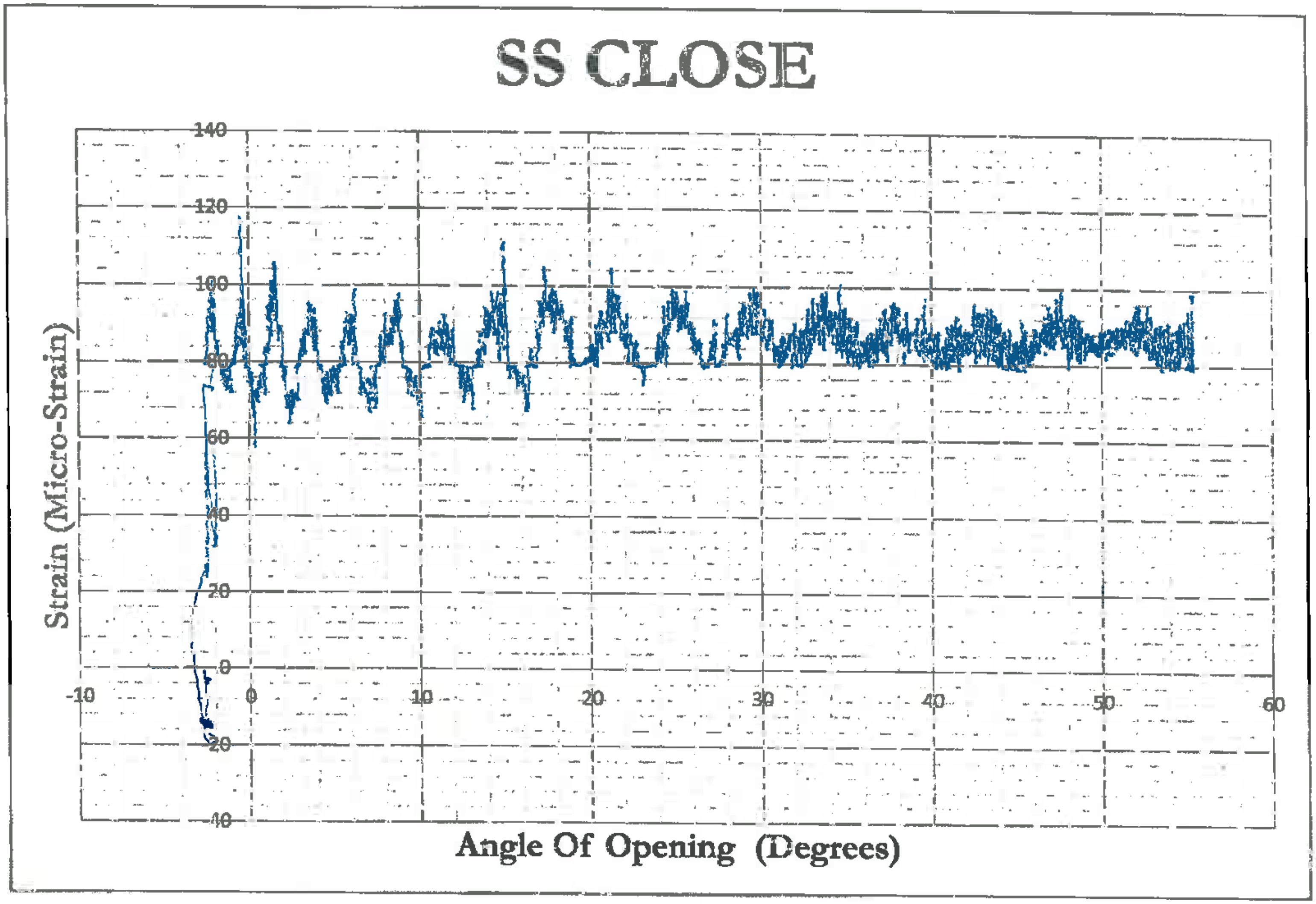
NS CLOSE



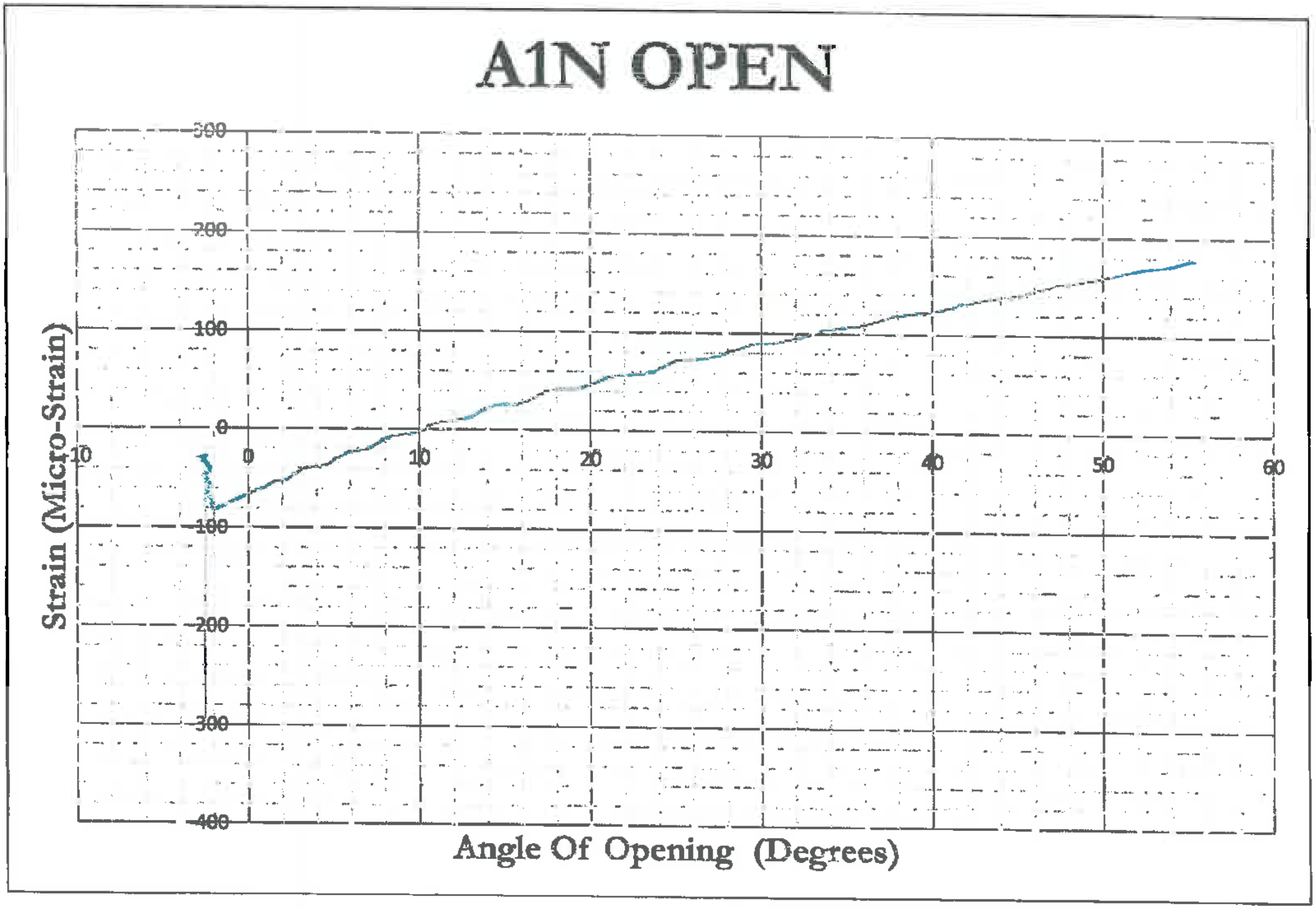
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE
SHIMSOUTFULLOPEN1



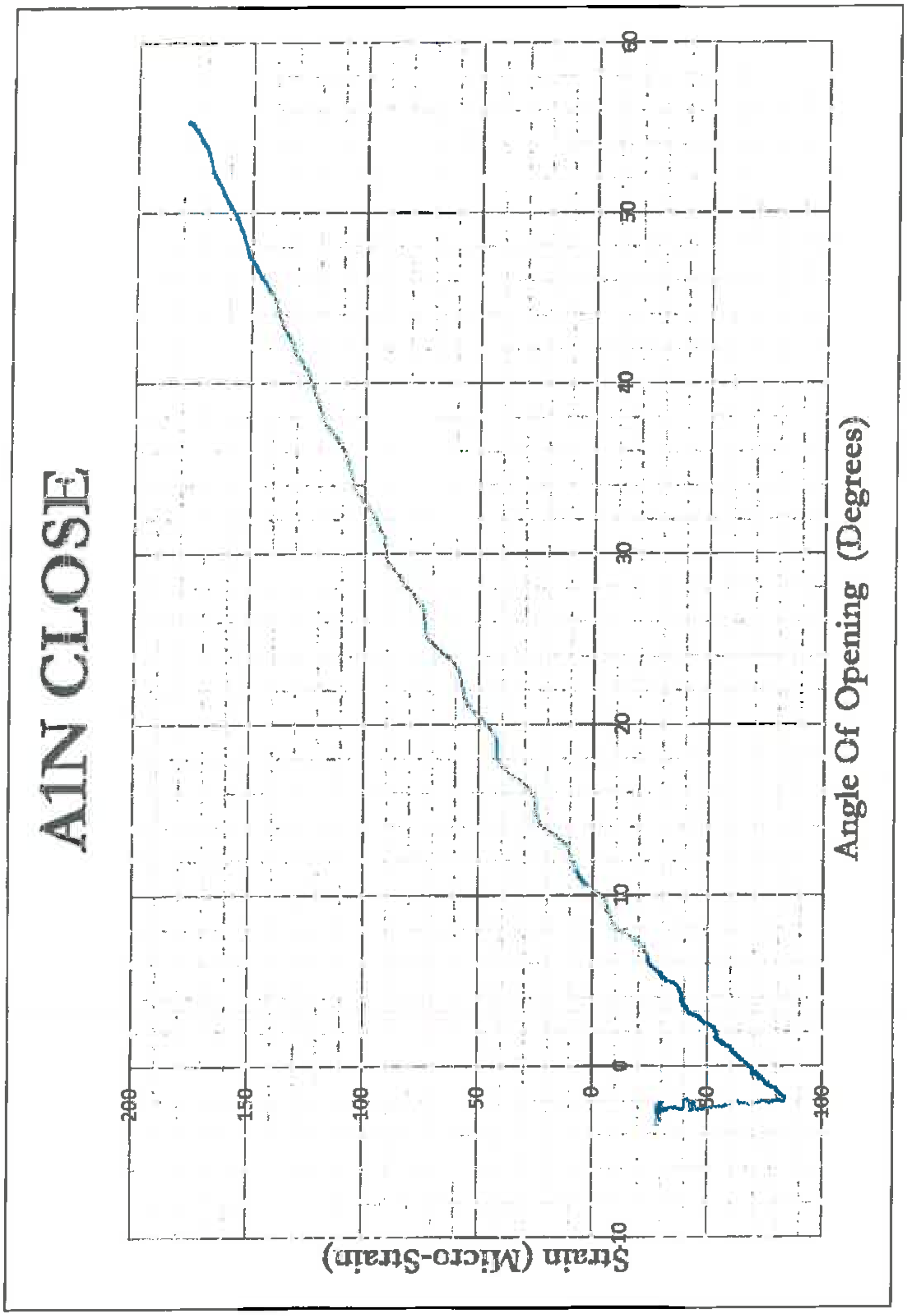
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE
SHIMSOUTFULLOPEN1



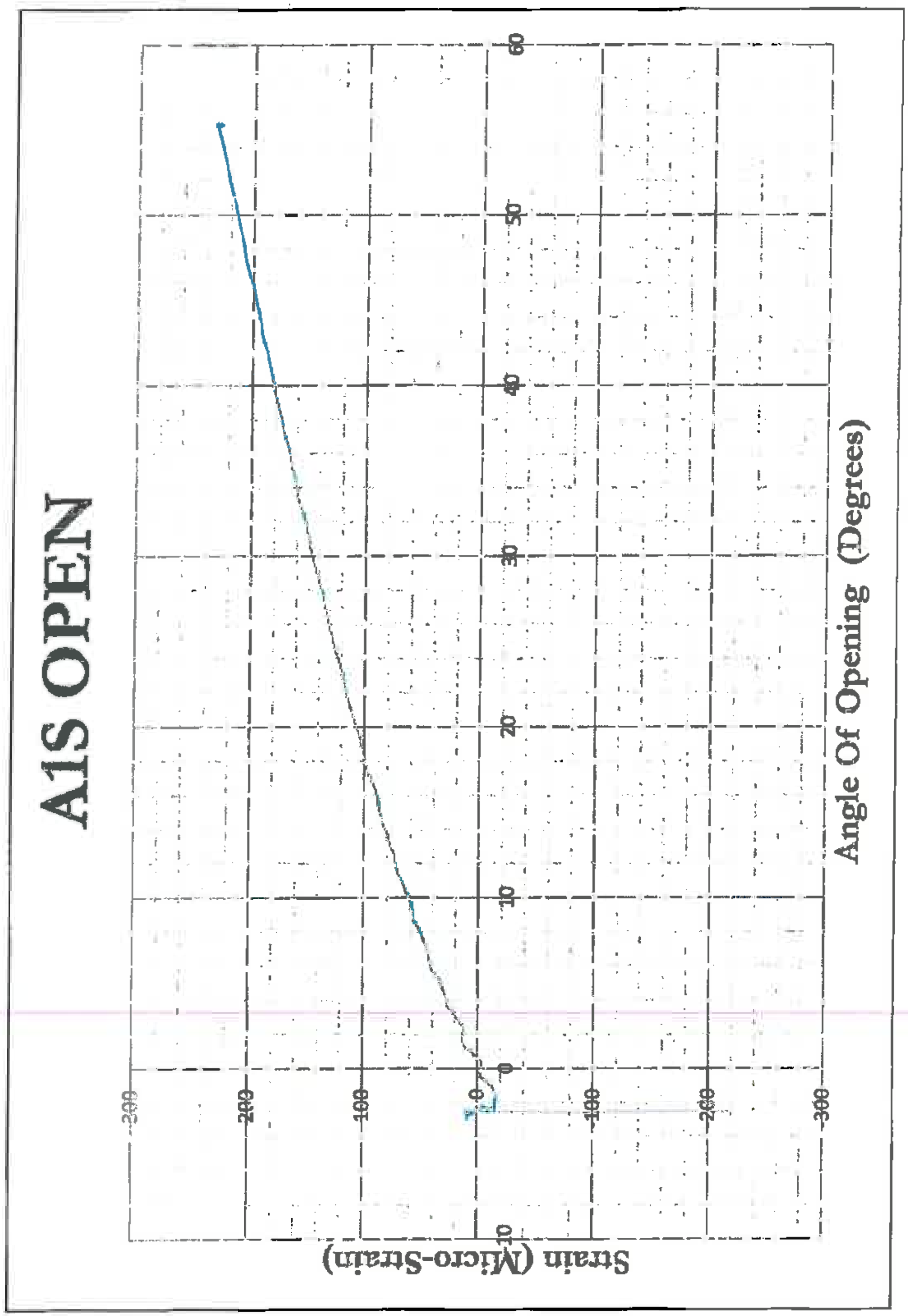
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE
SHIMSOUTFULLOPEN1



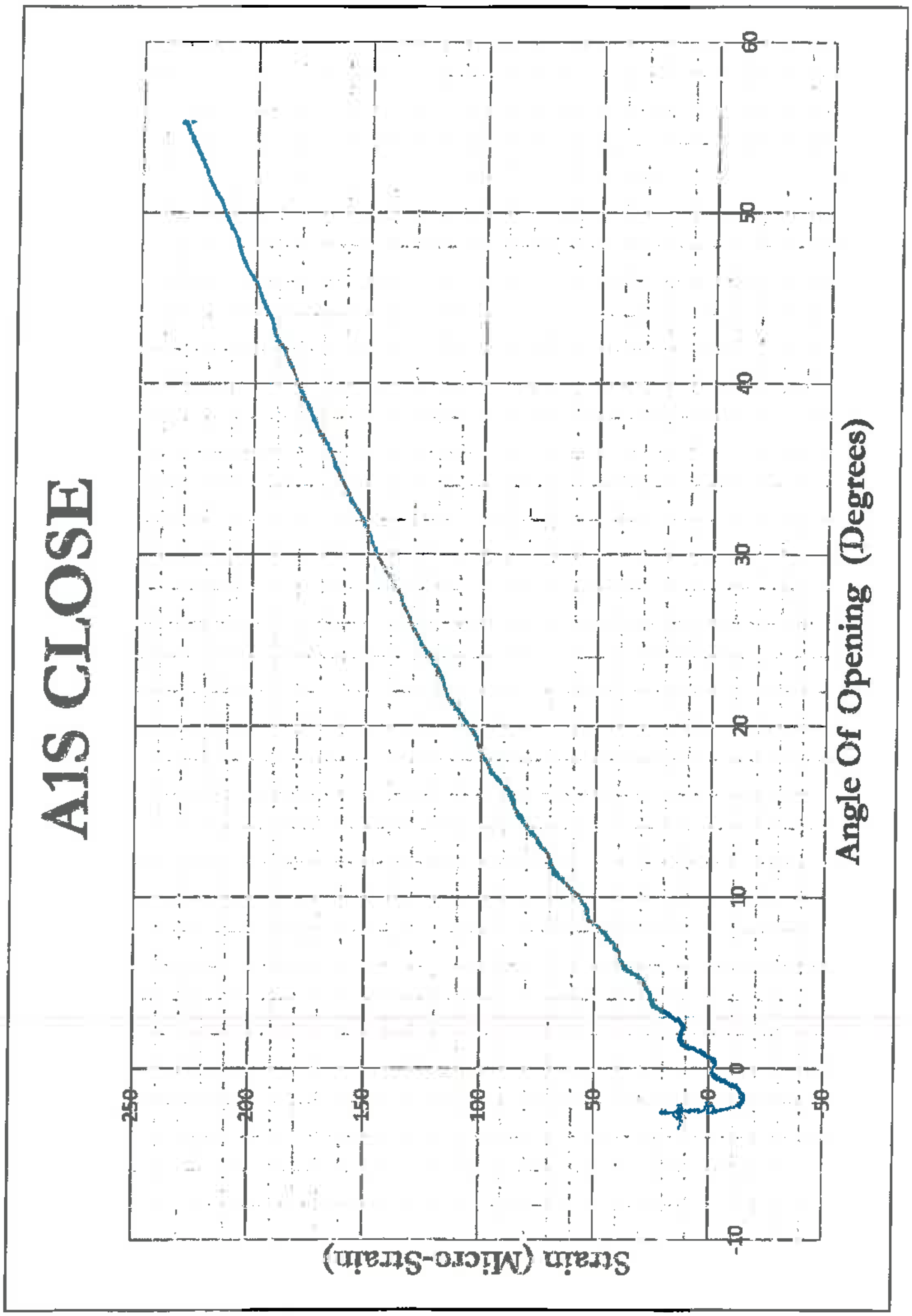
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE
SHIMSOUTFULLOPEN1



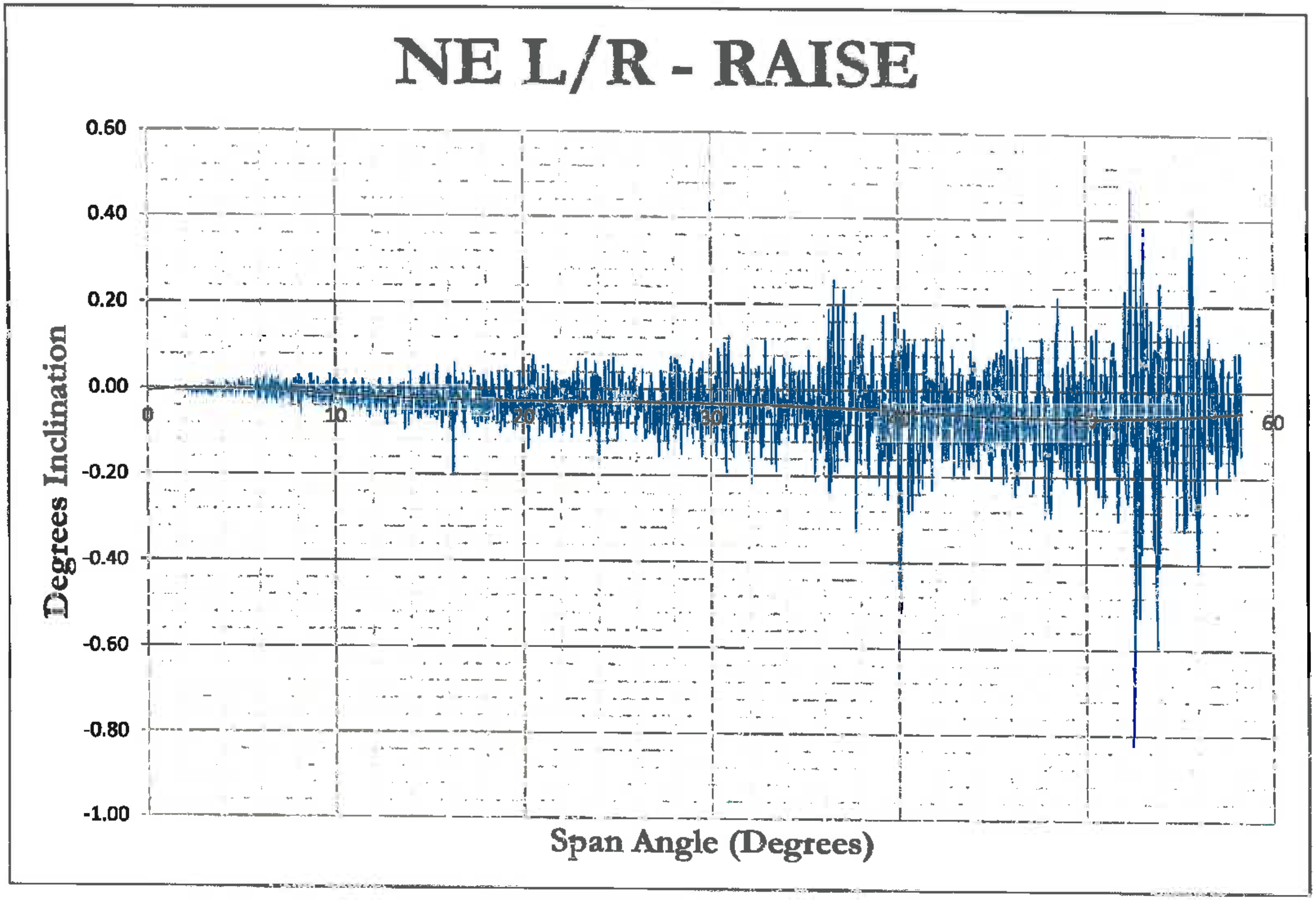
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE
SHIMSOUTFULLOPEN1



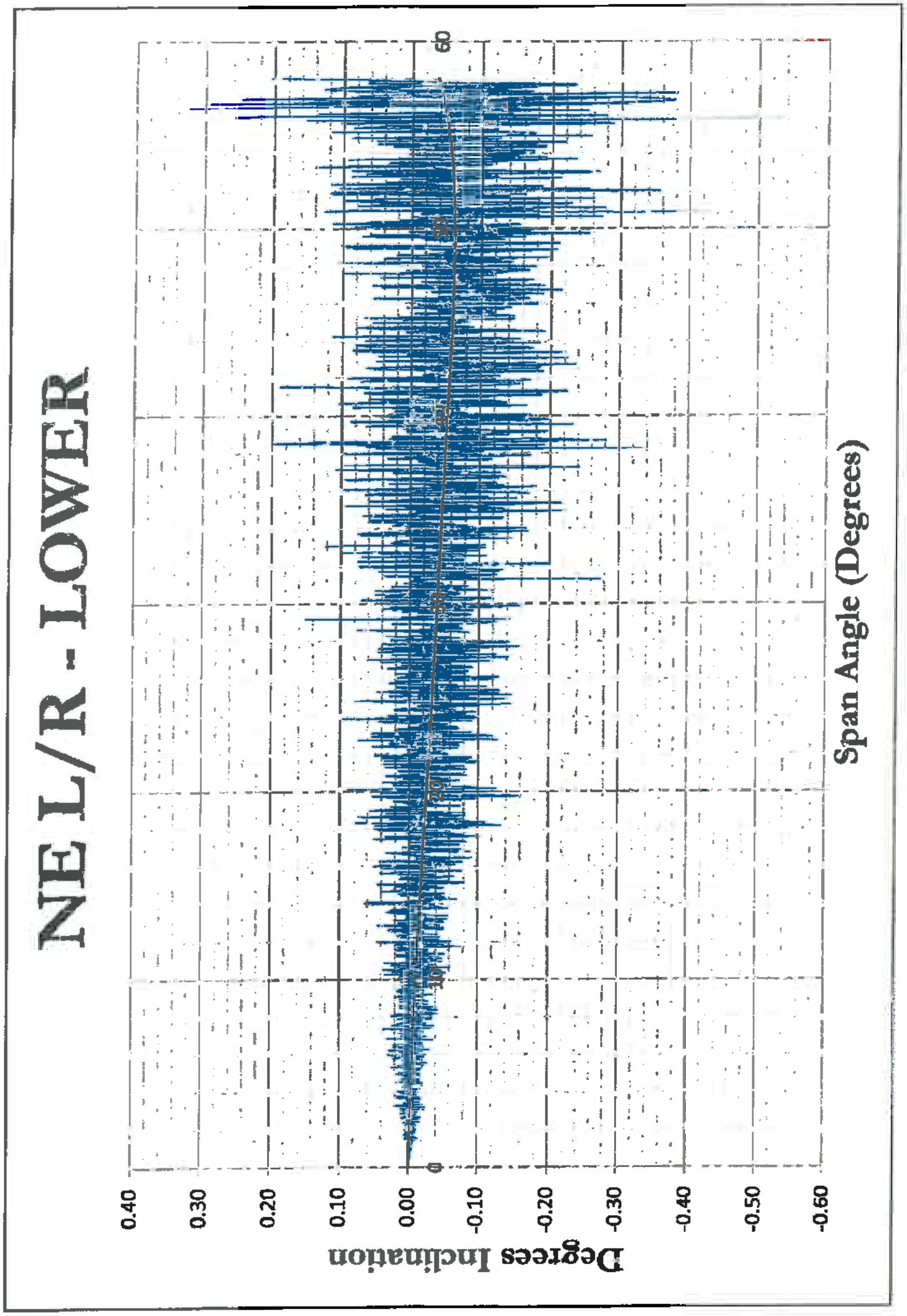
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
RALLSHIM10AND10GAUGE
SHIMSOUTFULLOPEN1



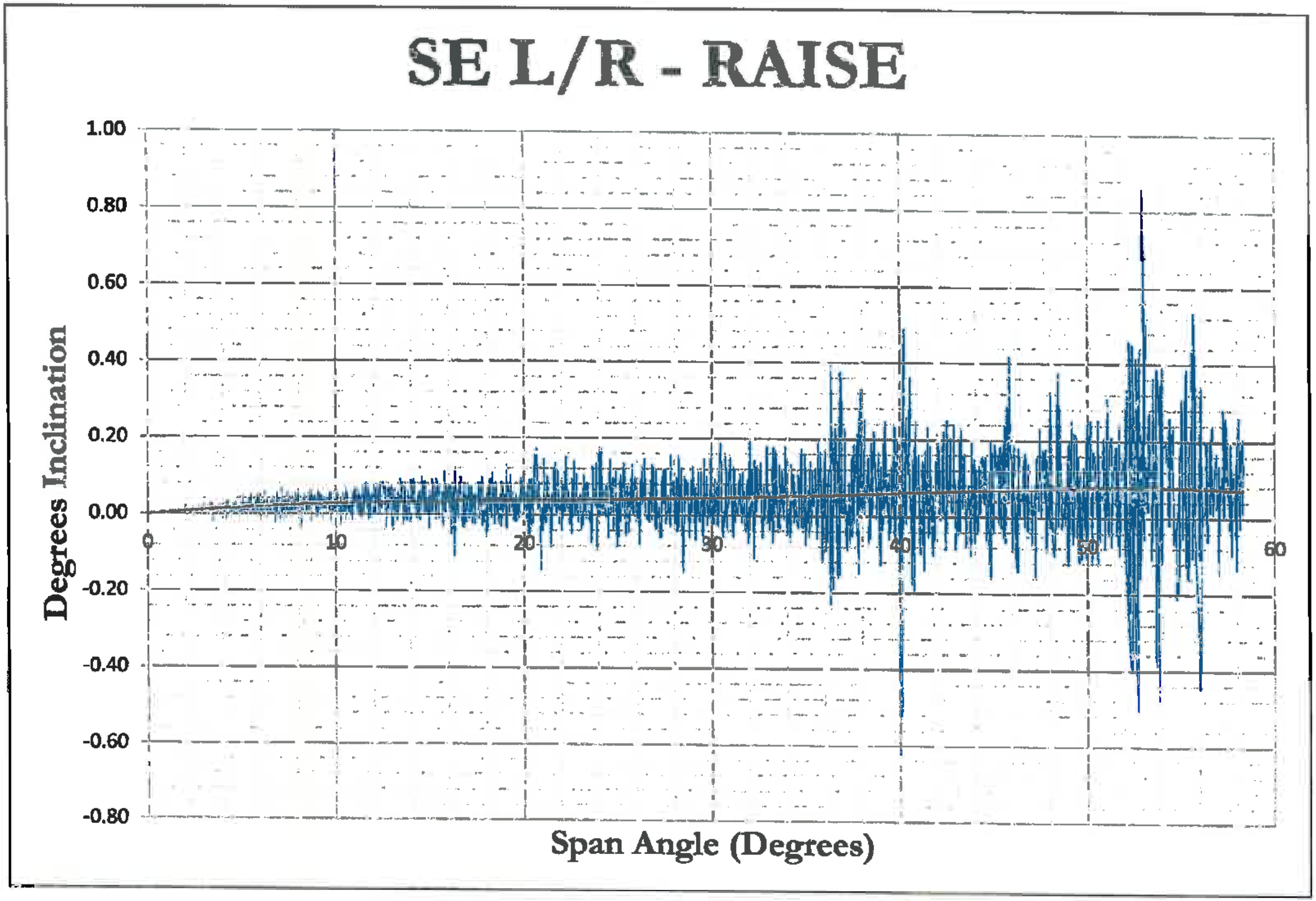
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #1



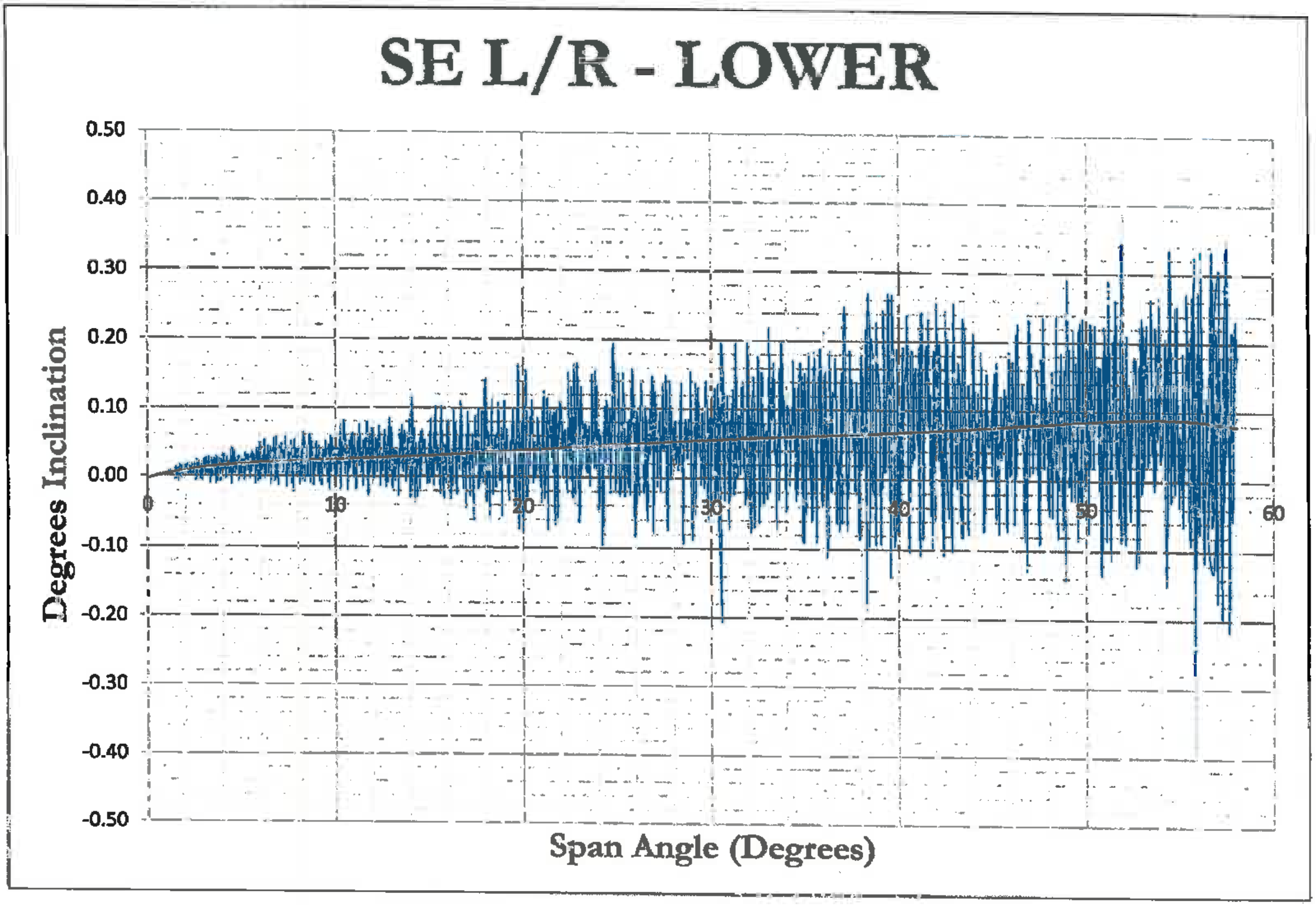
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #1



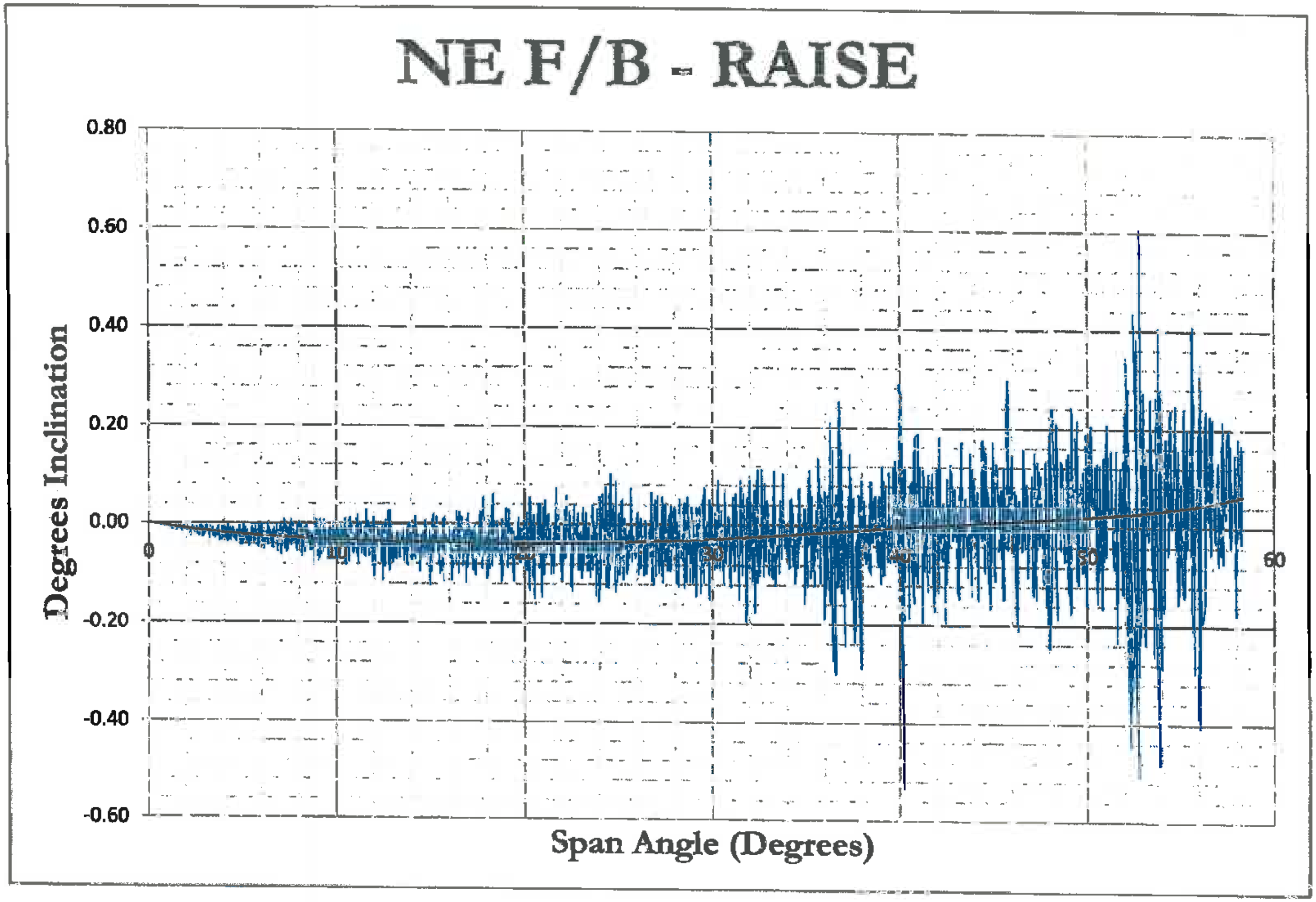
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #1



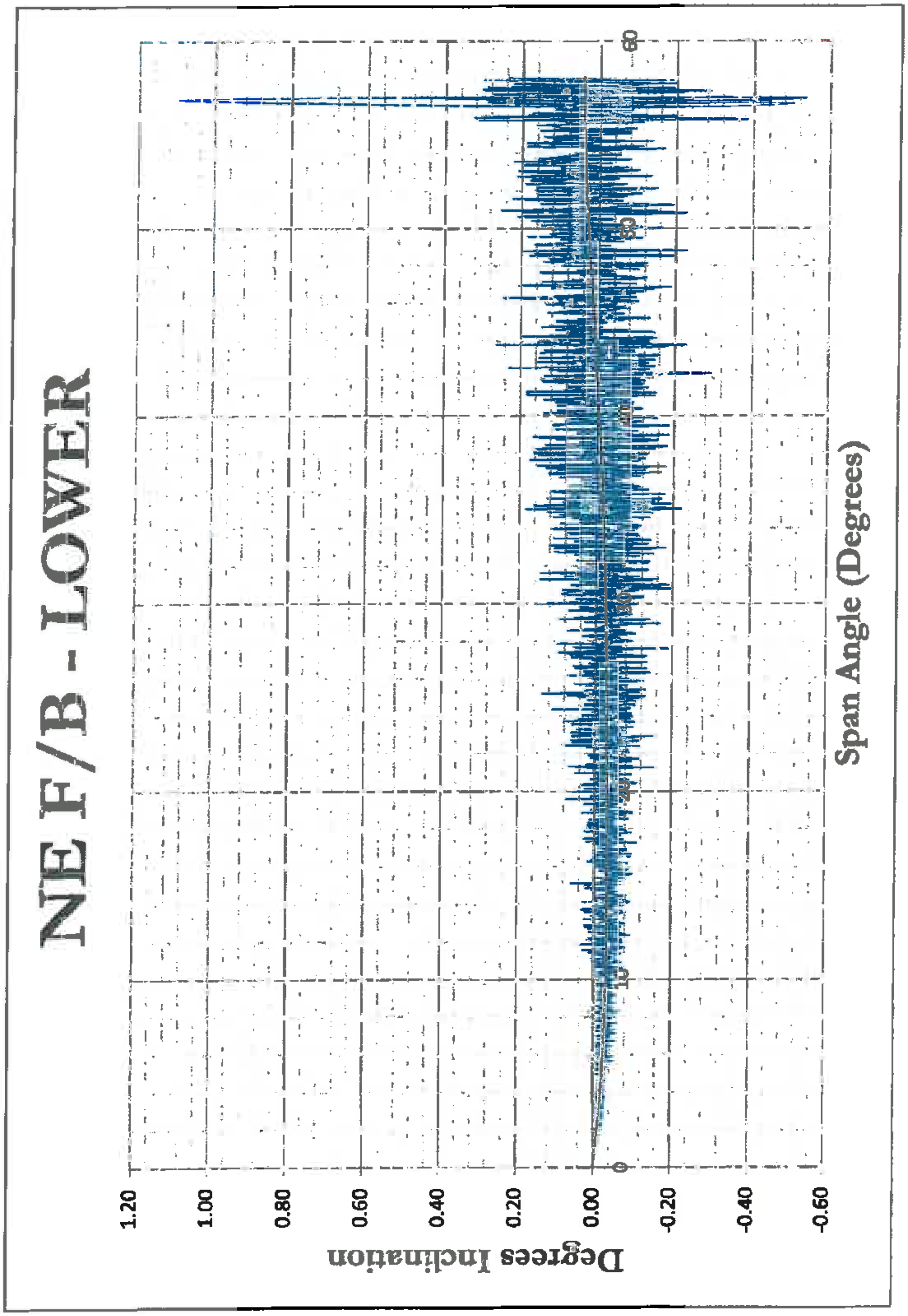
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #1



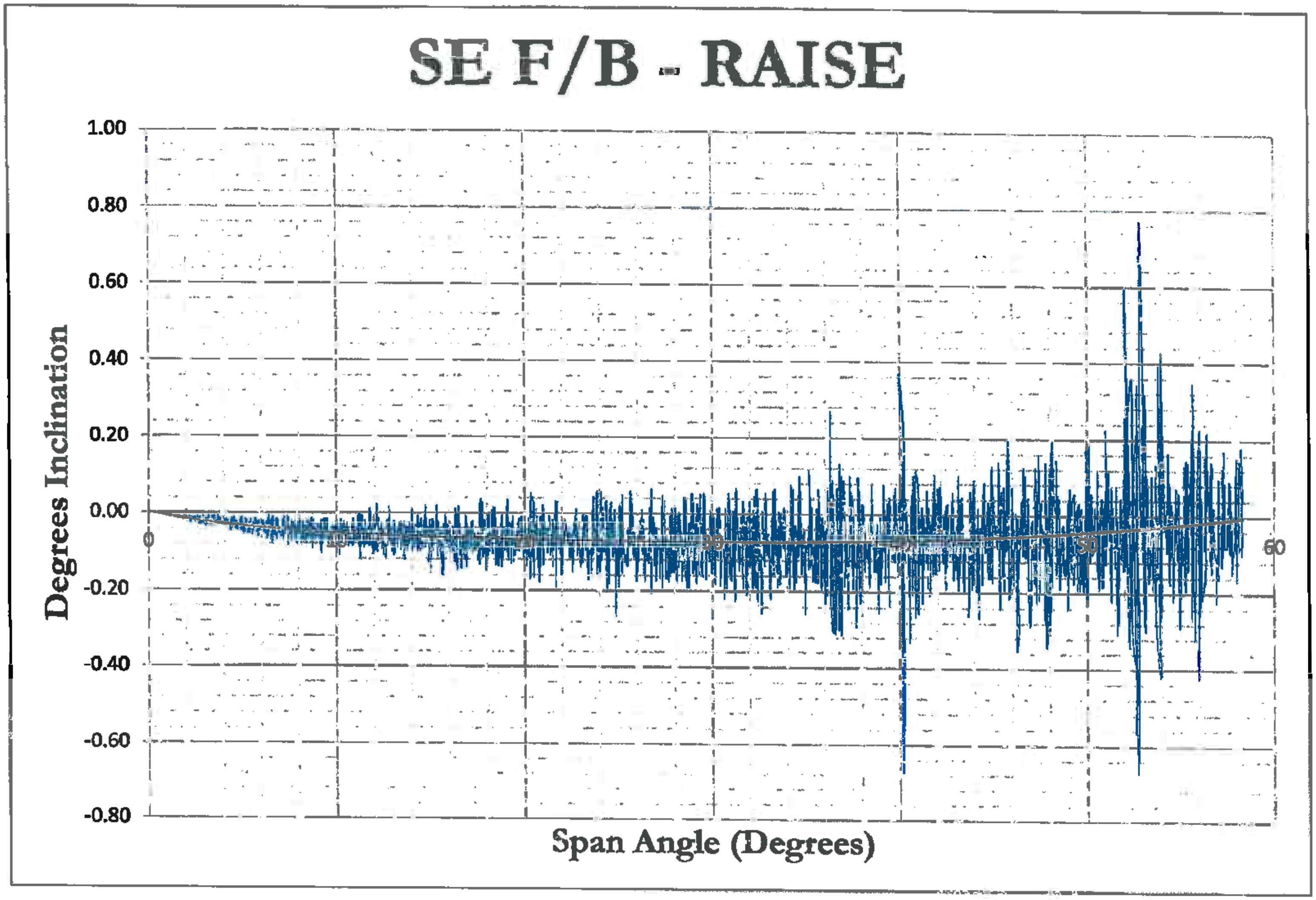
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #1



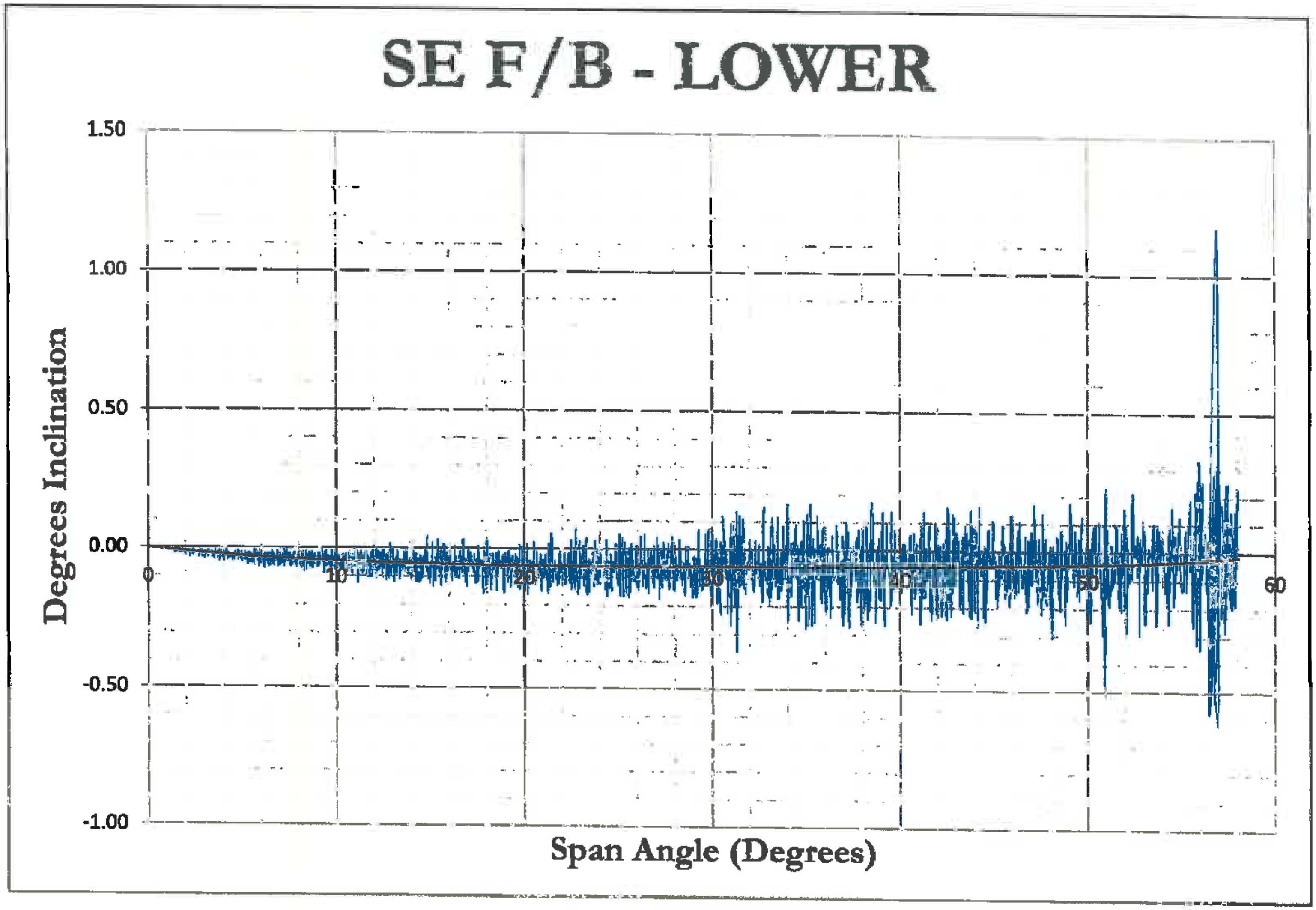
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #1



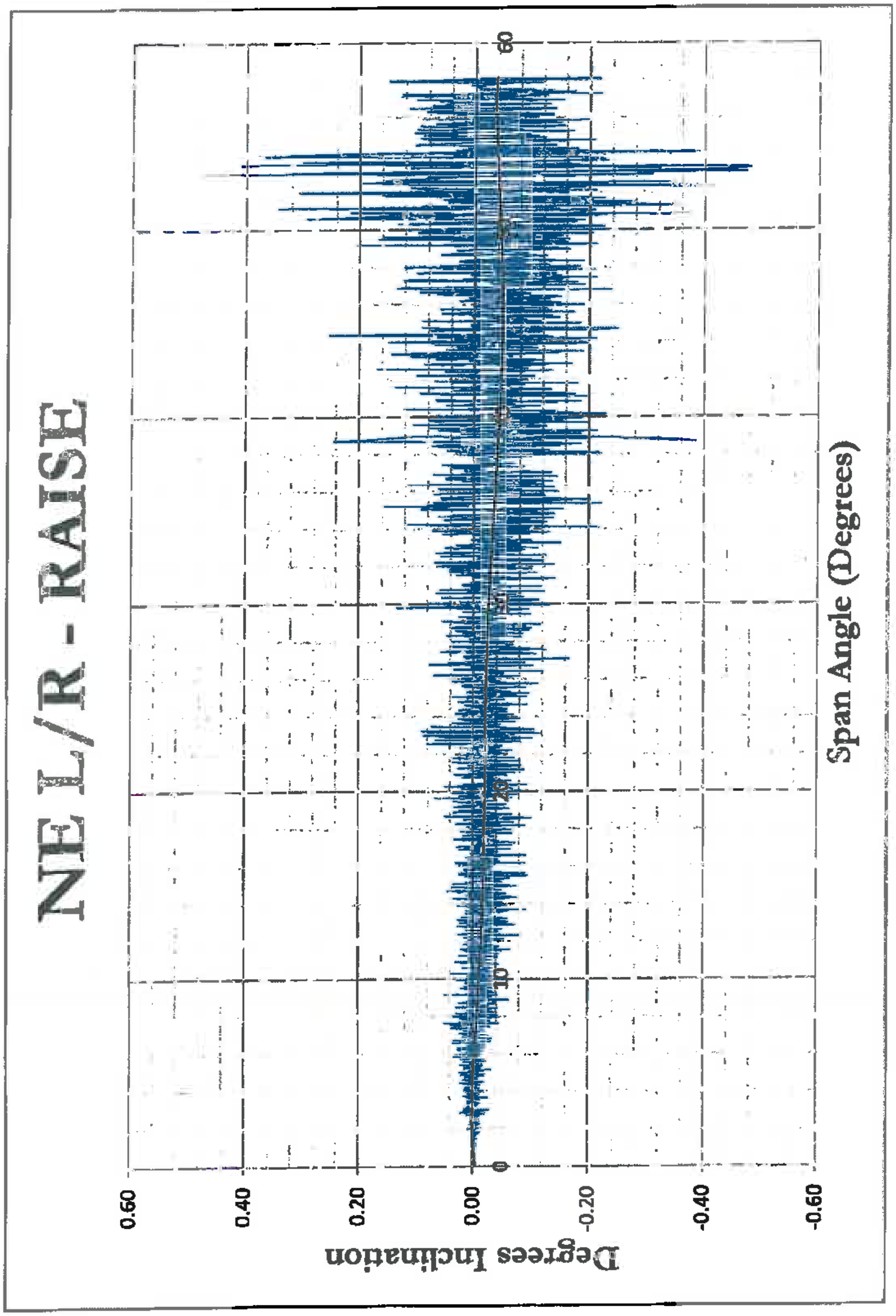
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #1



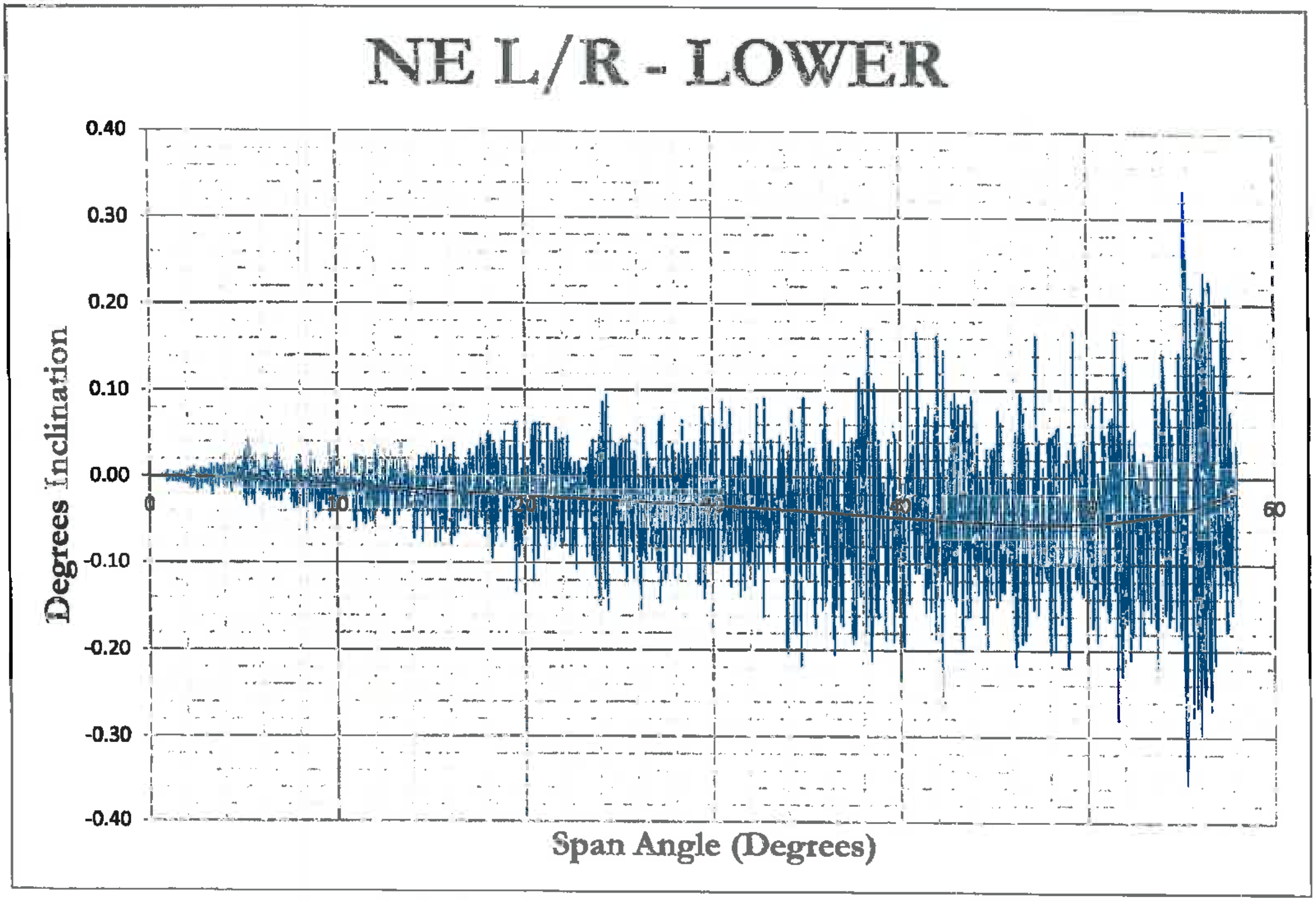
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #1



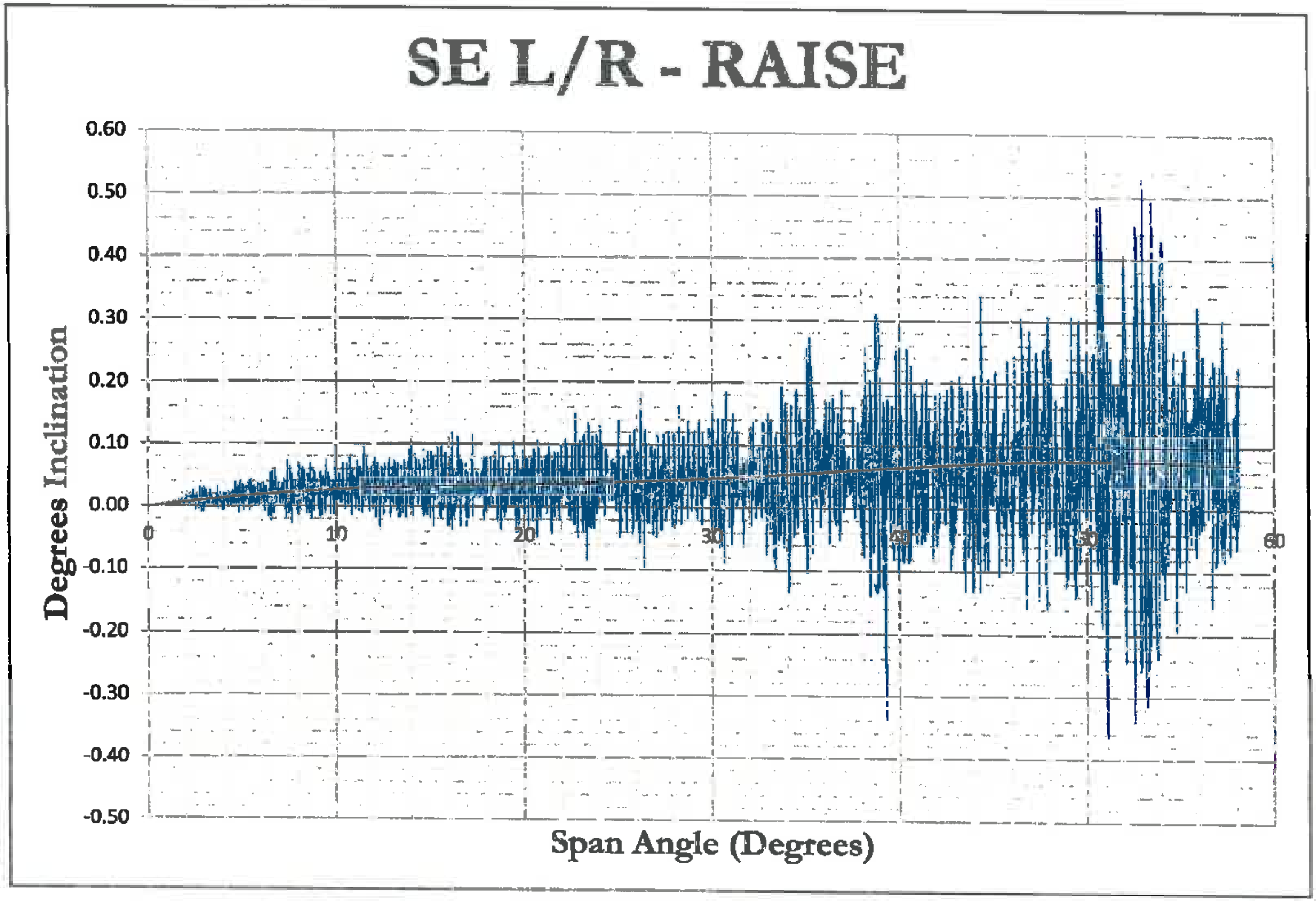
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #2



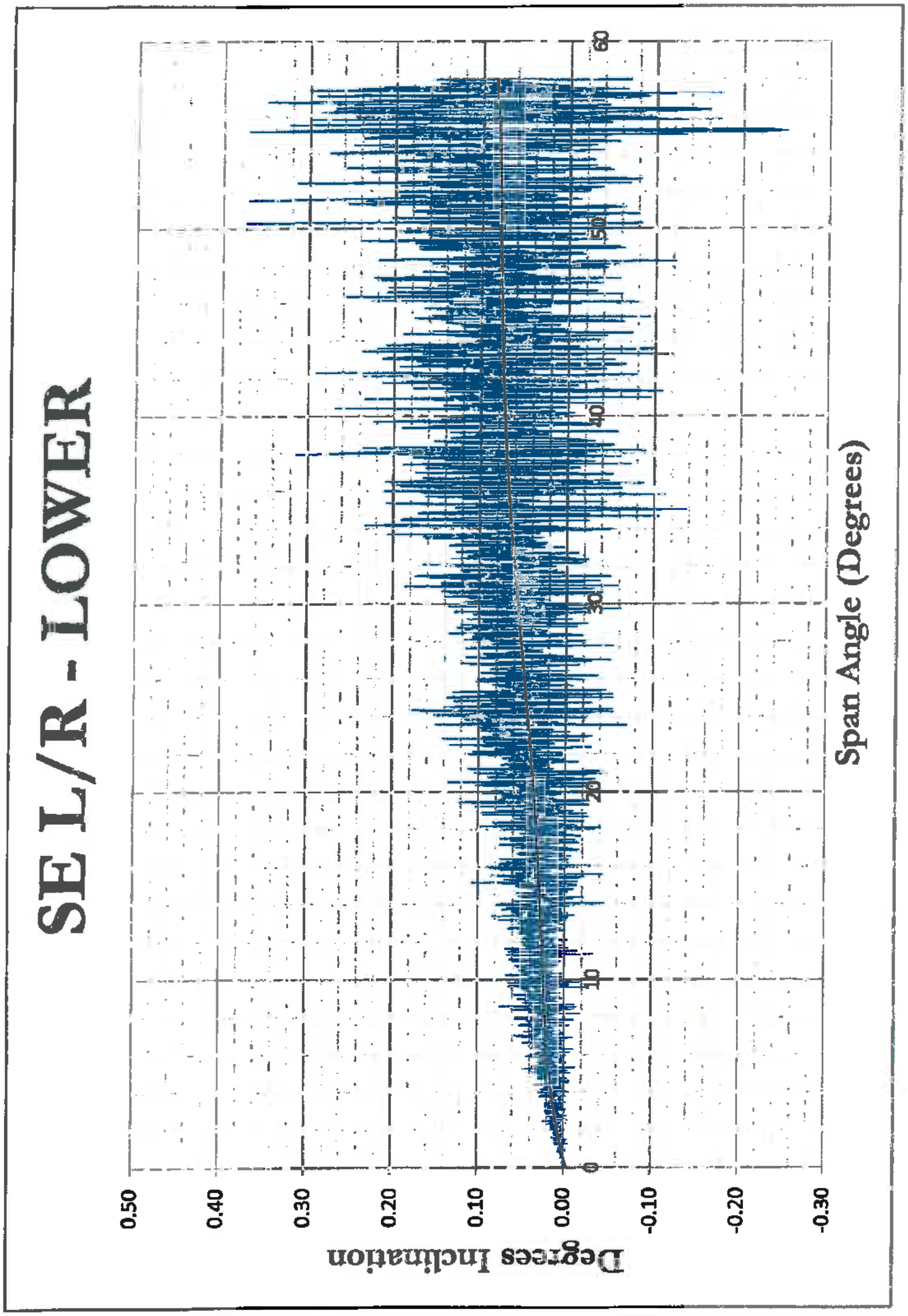
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #2



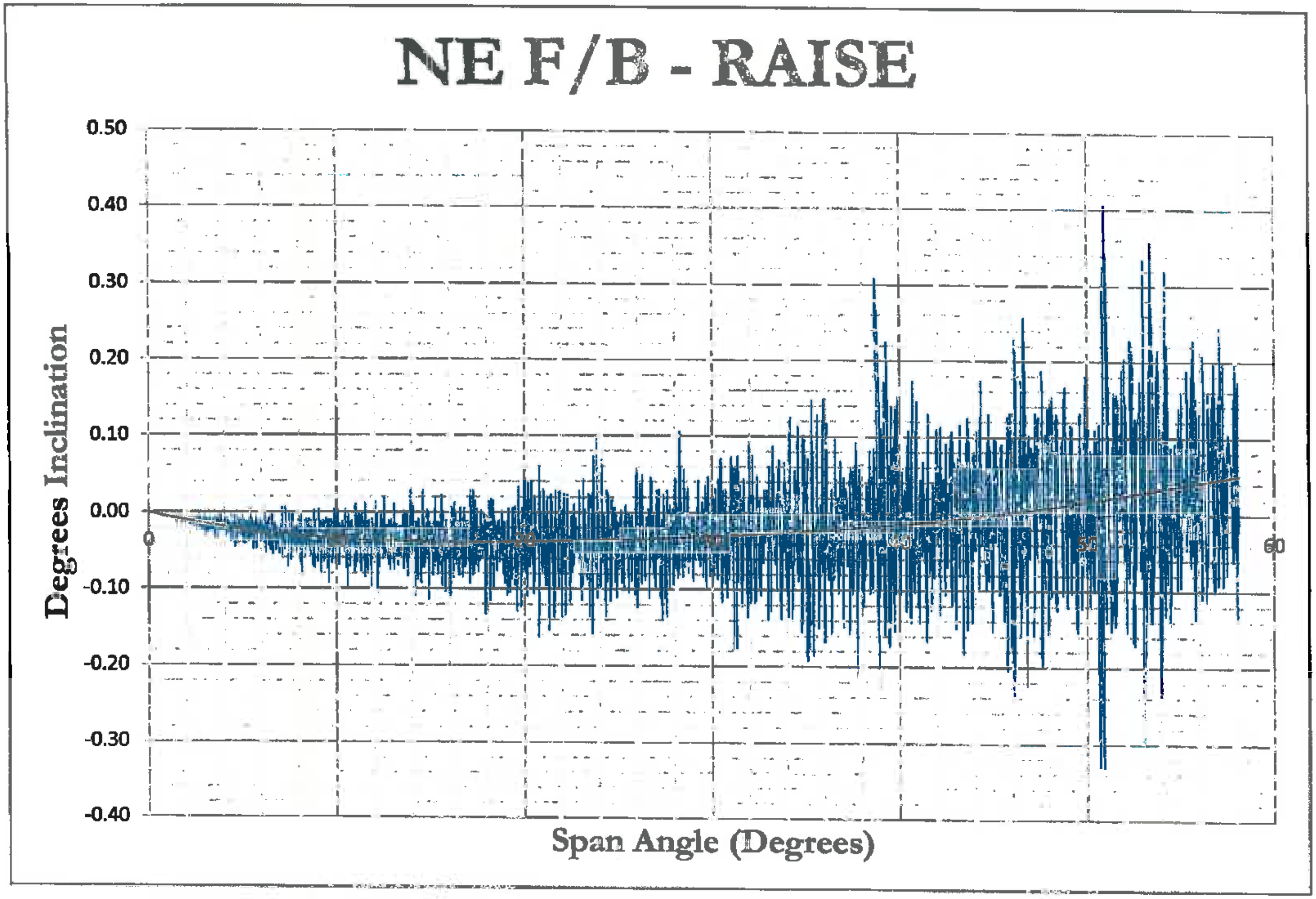
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #2



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #2



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #2



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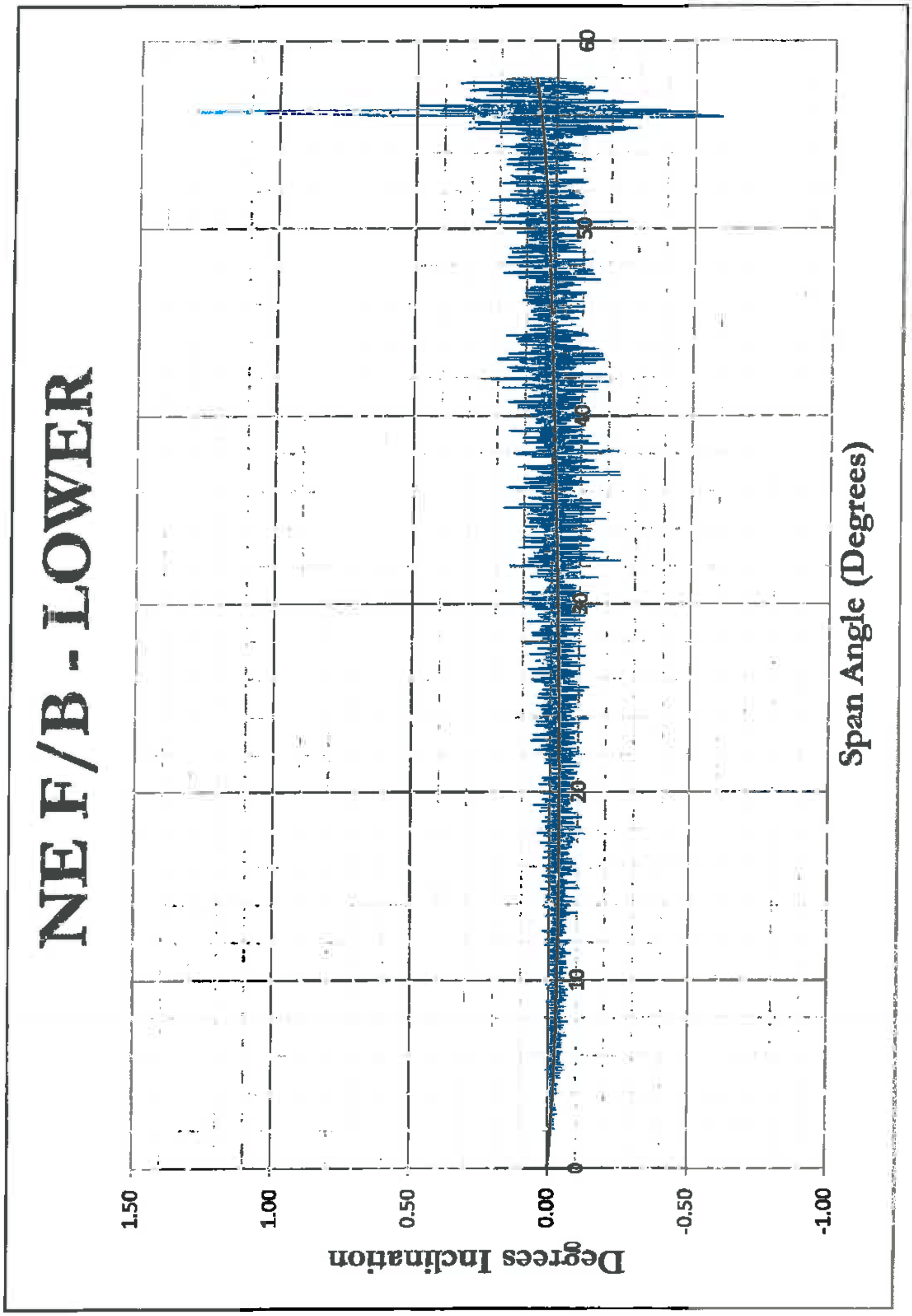
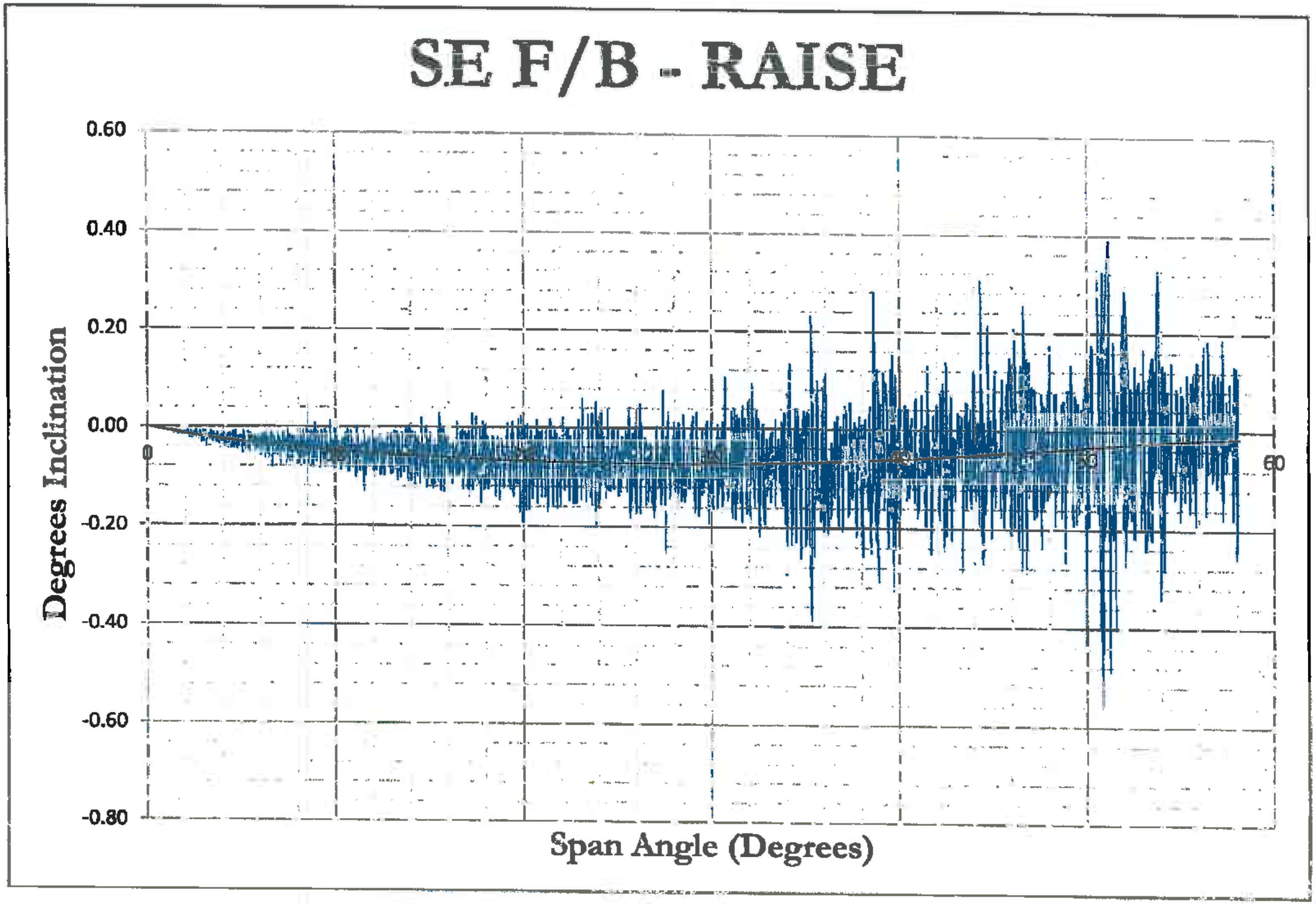
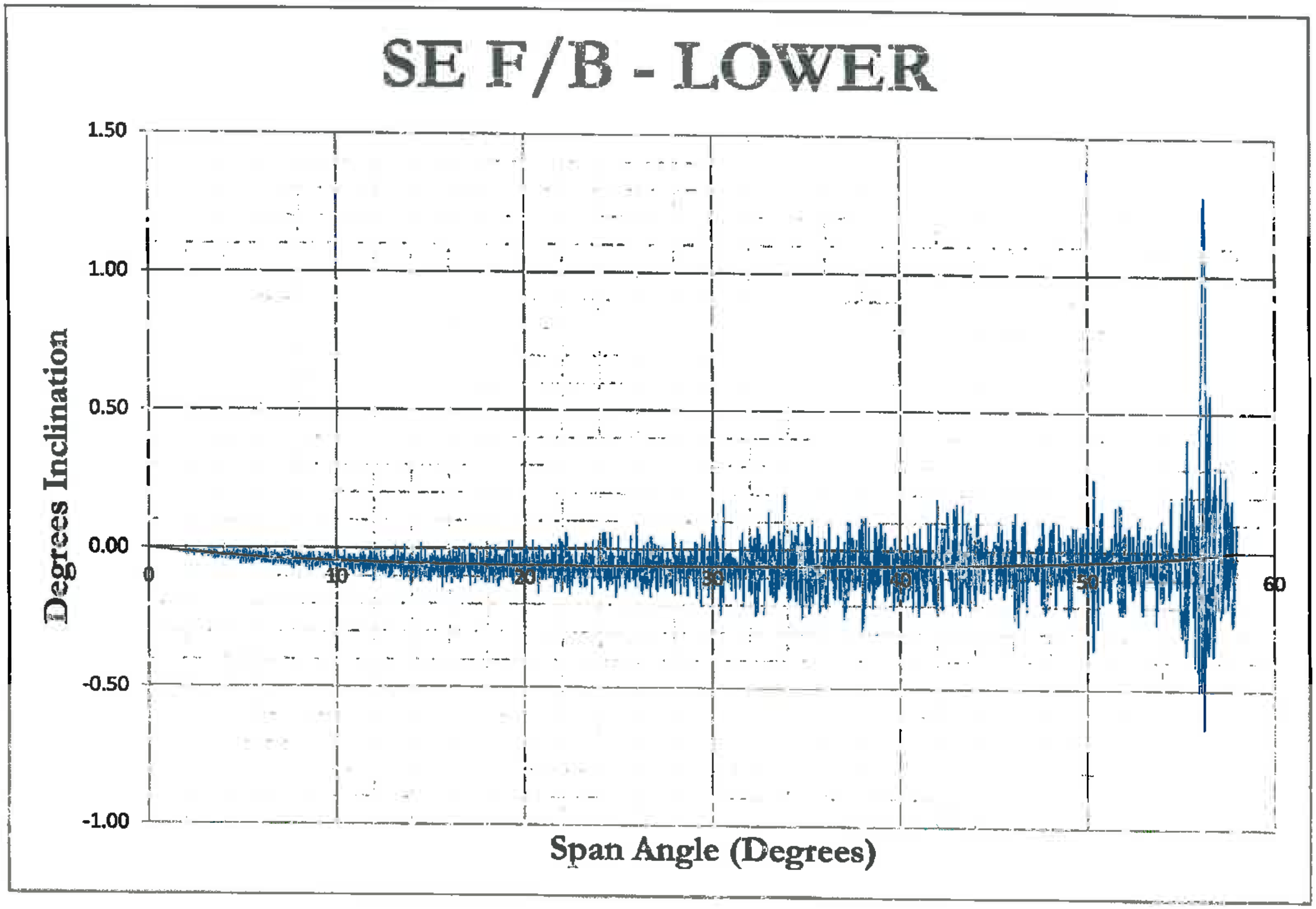
EAST BRIDGE
ANALOG DATA TRIAL #2



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #2



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #2



BROADWAY BRIDGE - 02720.00
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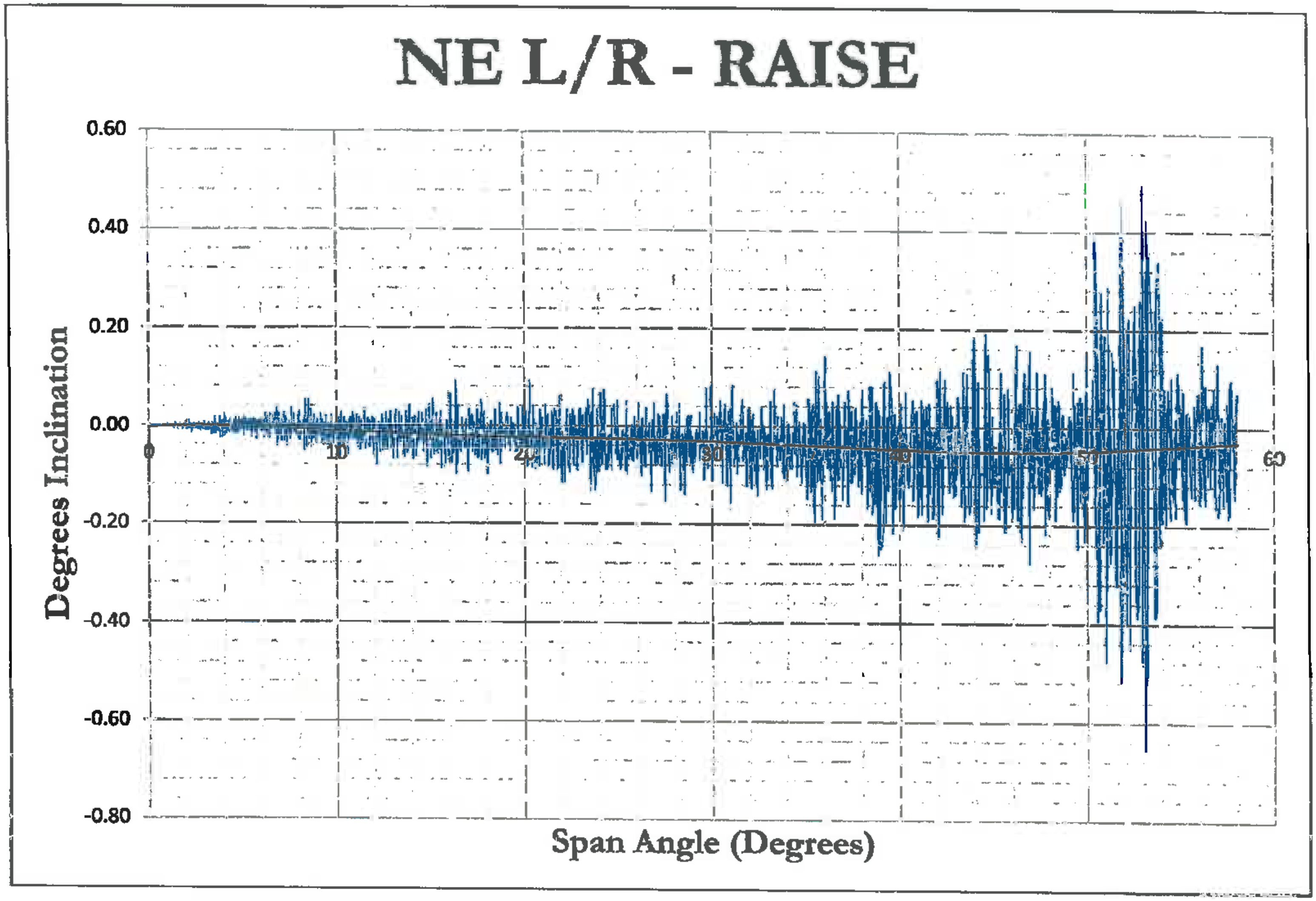

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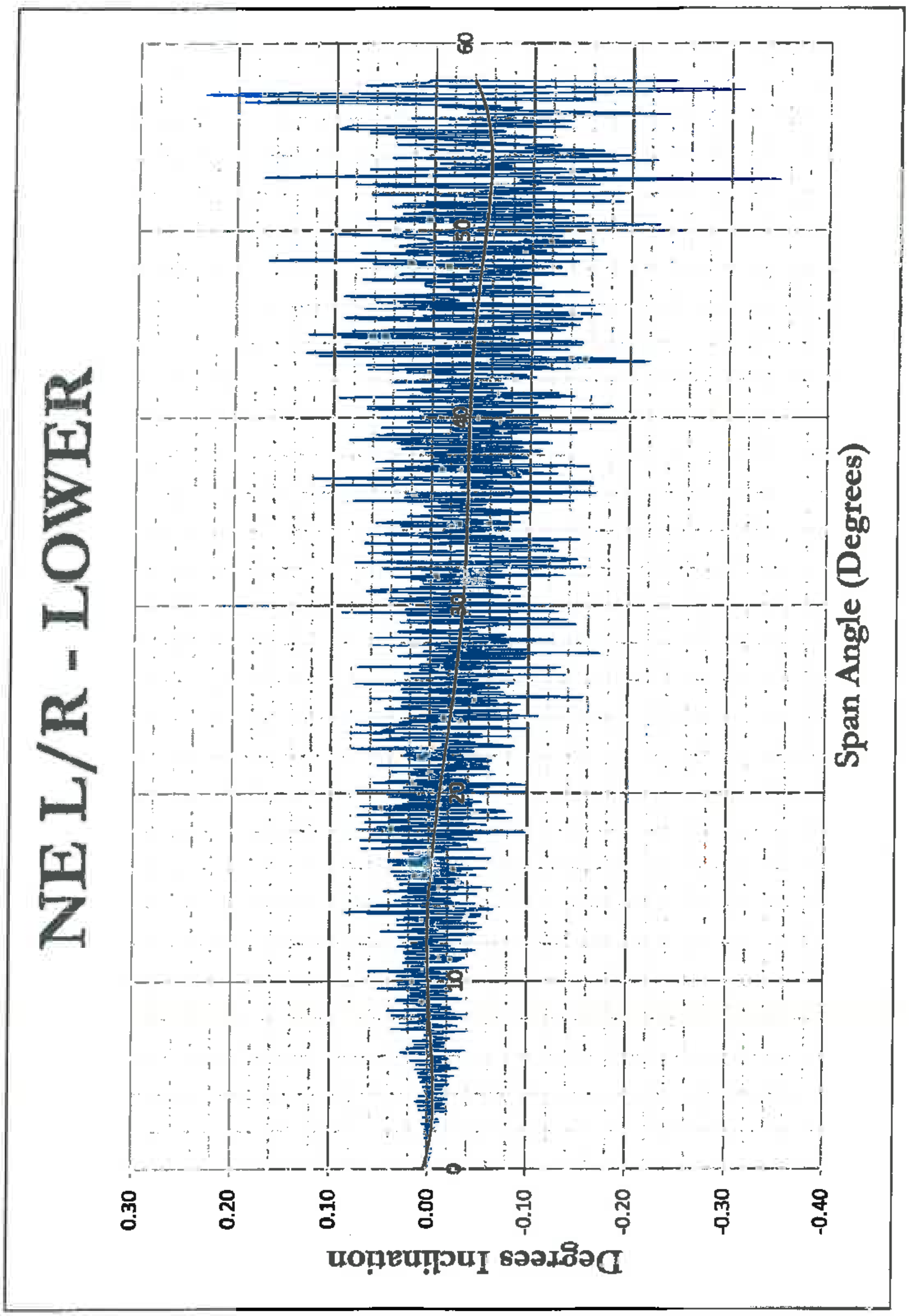

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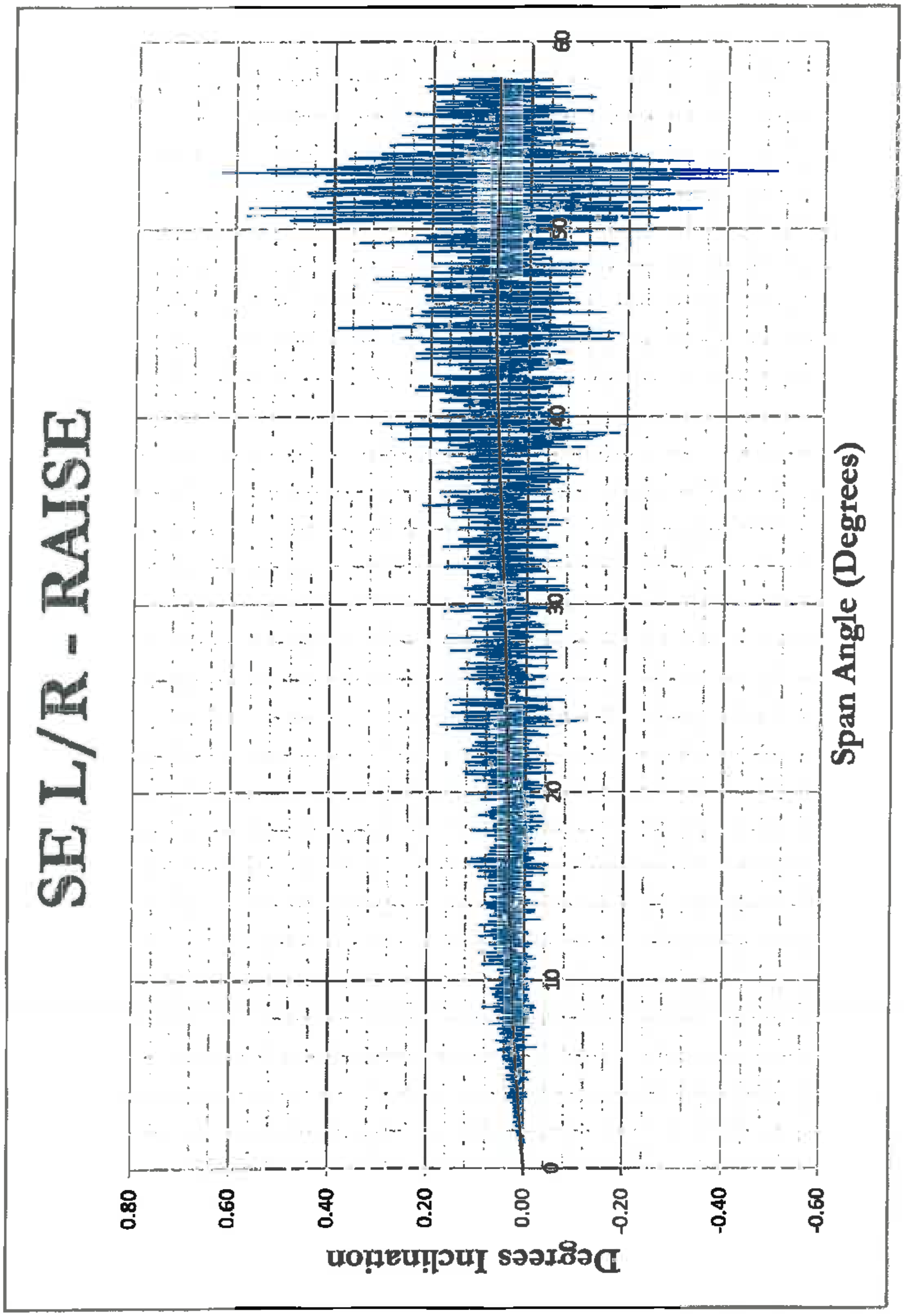
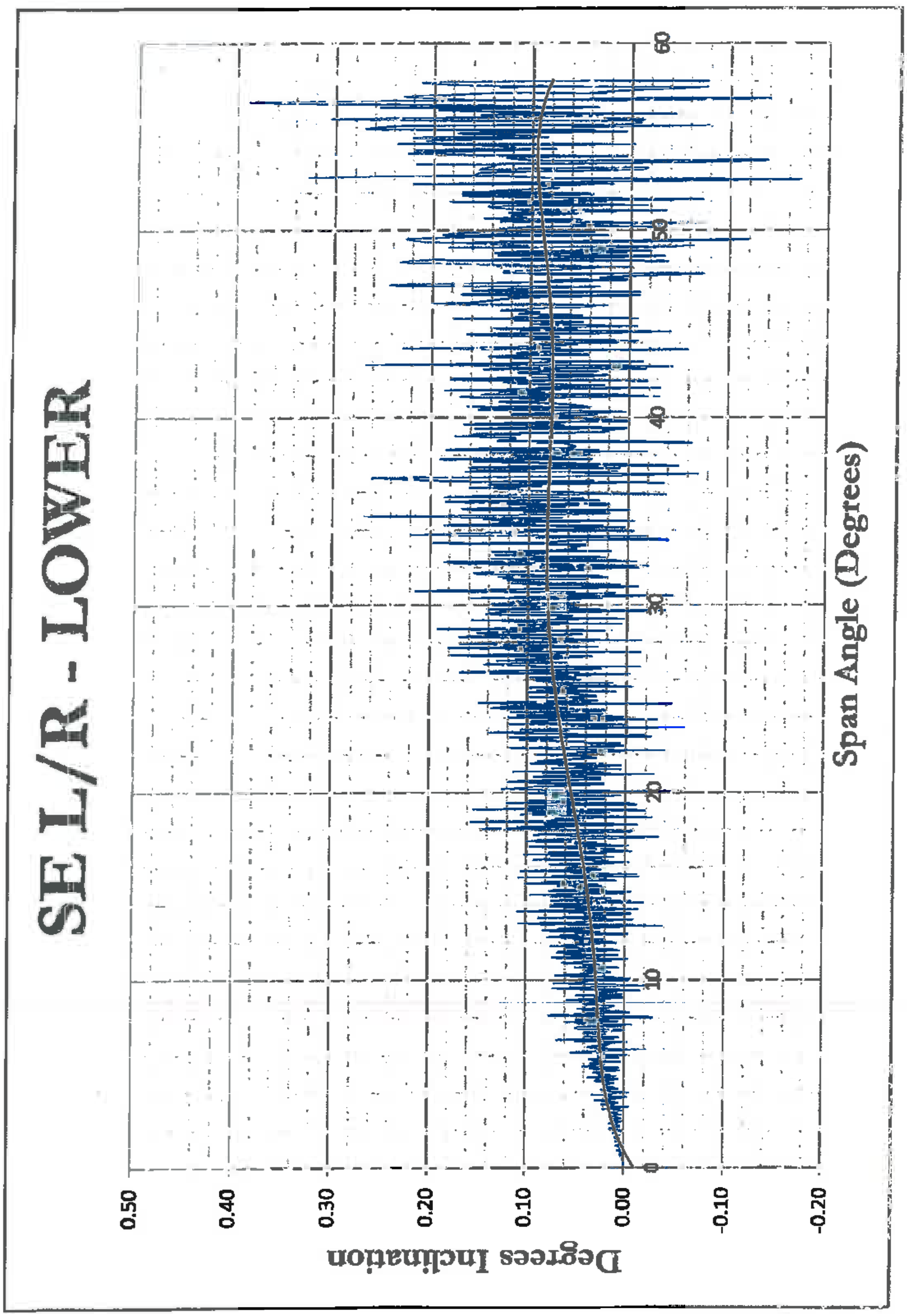
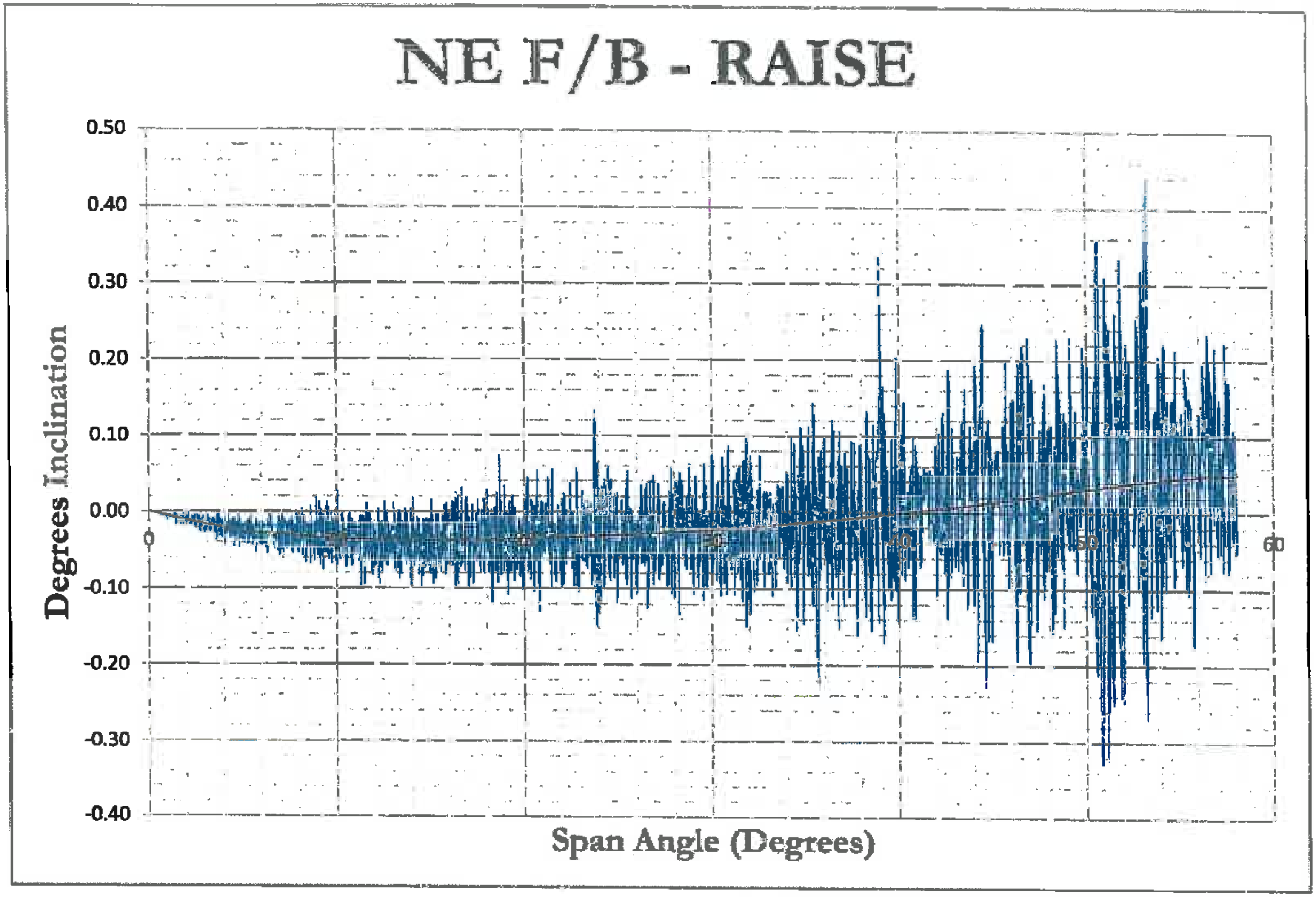


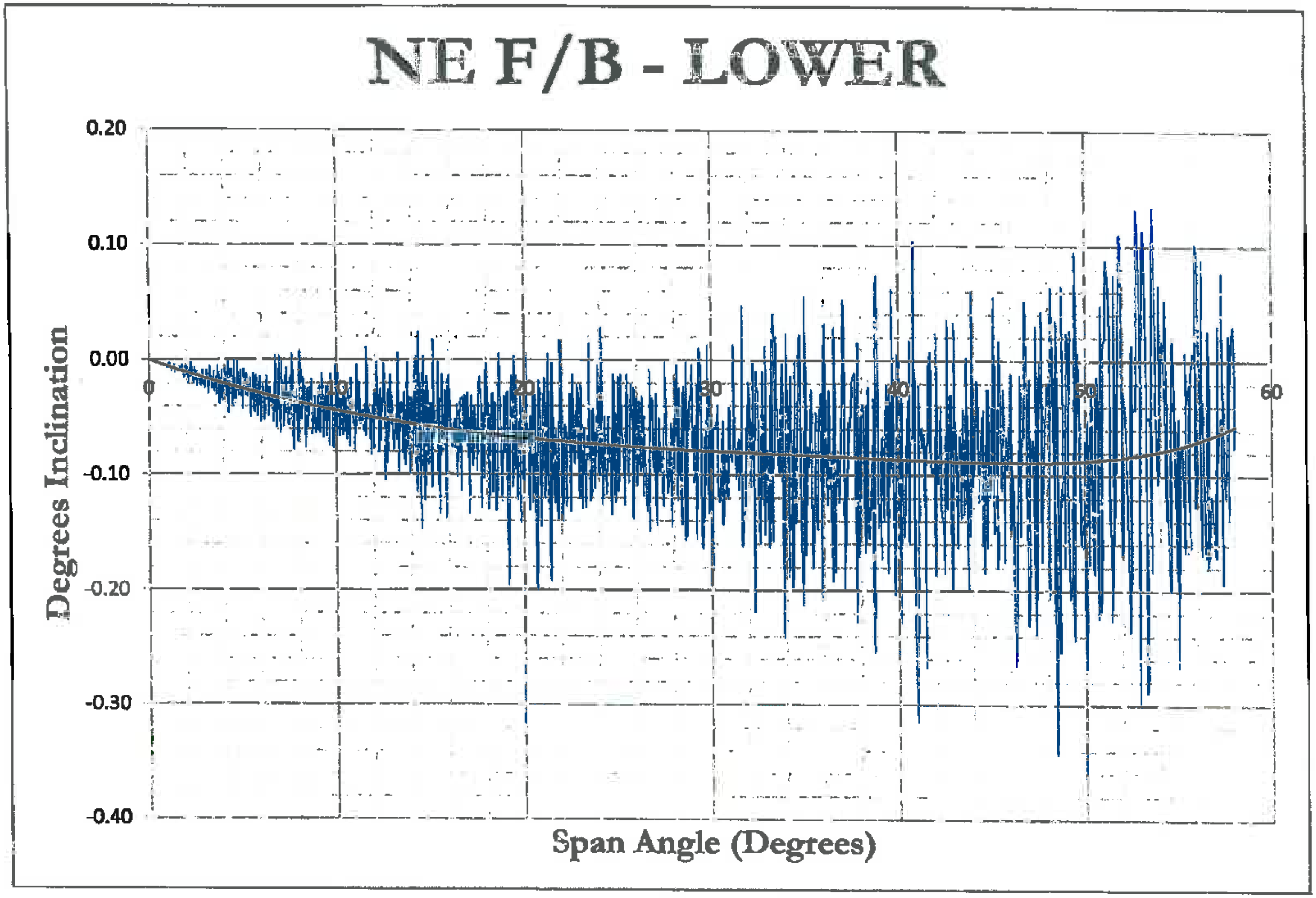
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #3



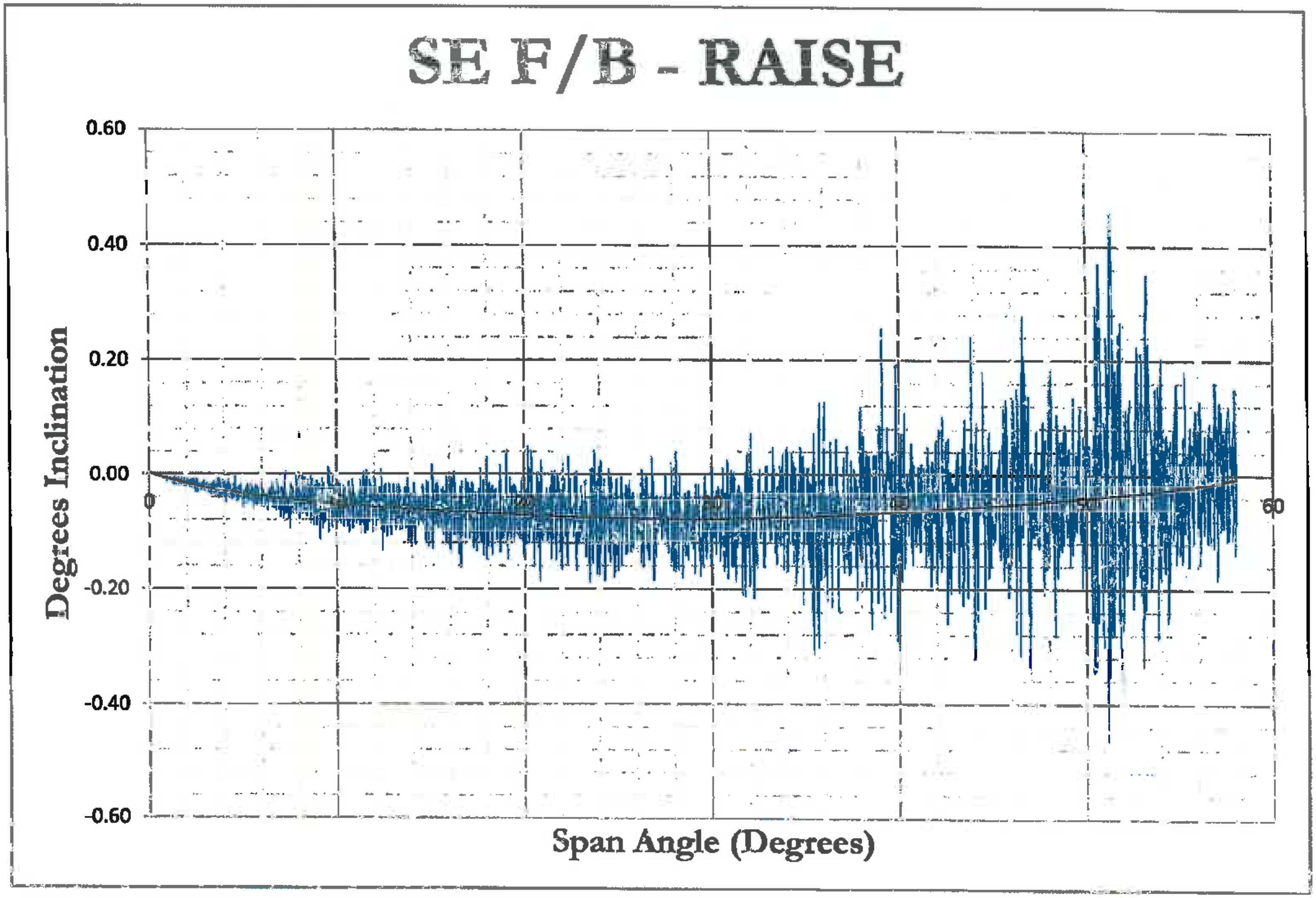
BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #3



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #3



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #3



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EAST BRIDGE
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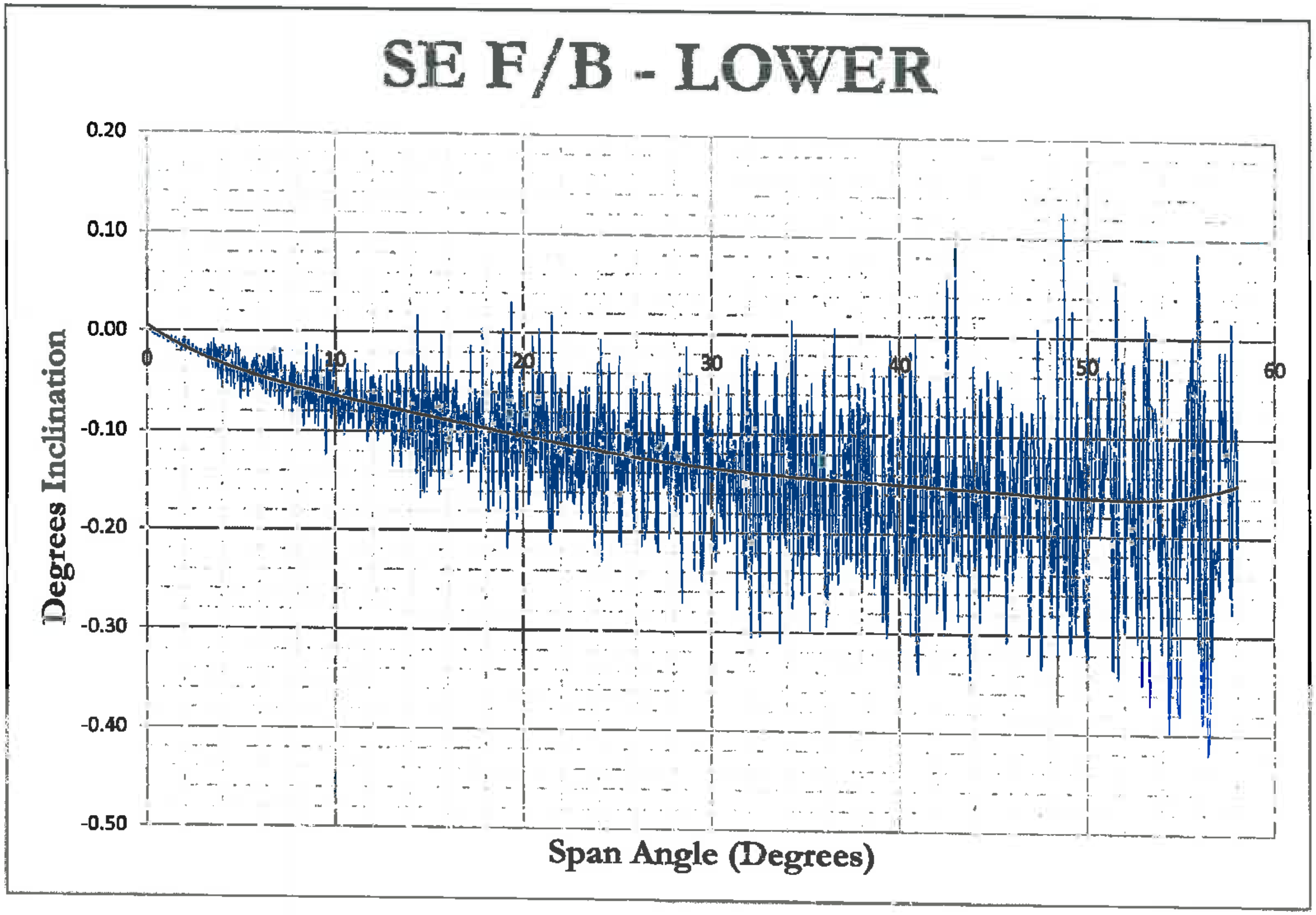
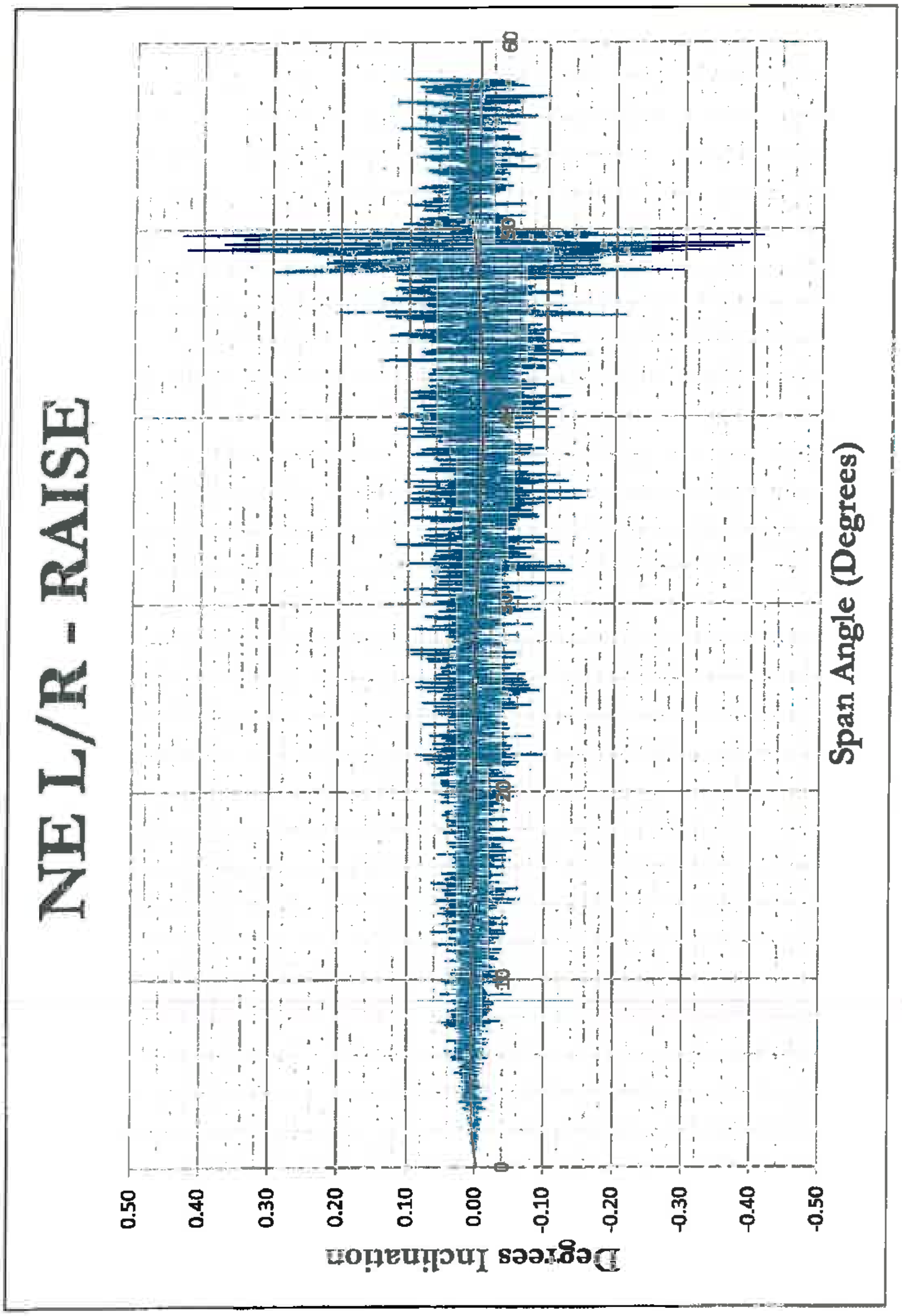


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #4



BROADWAY BRIDGE - 02720.00
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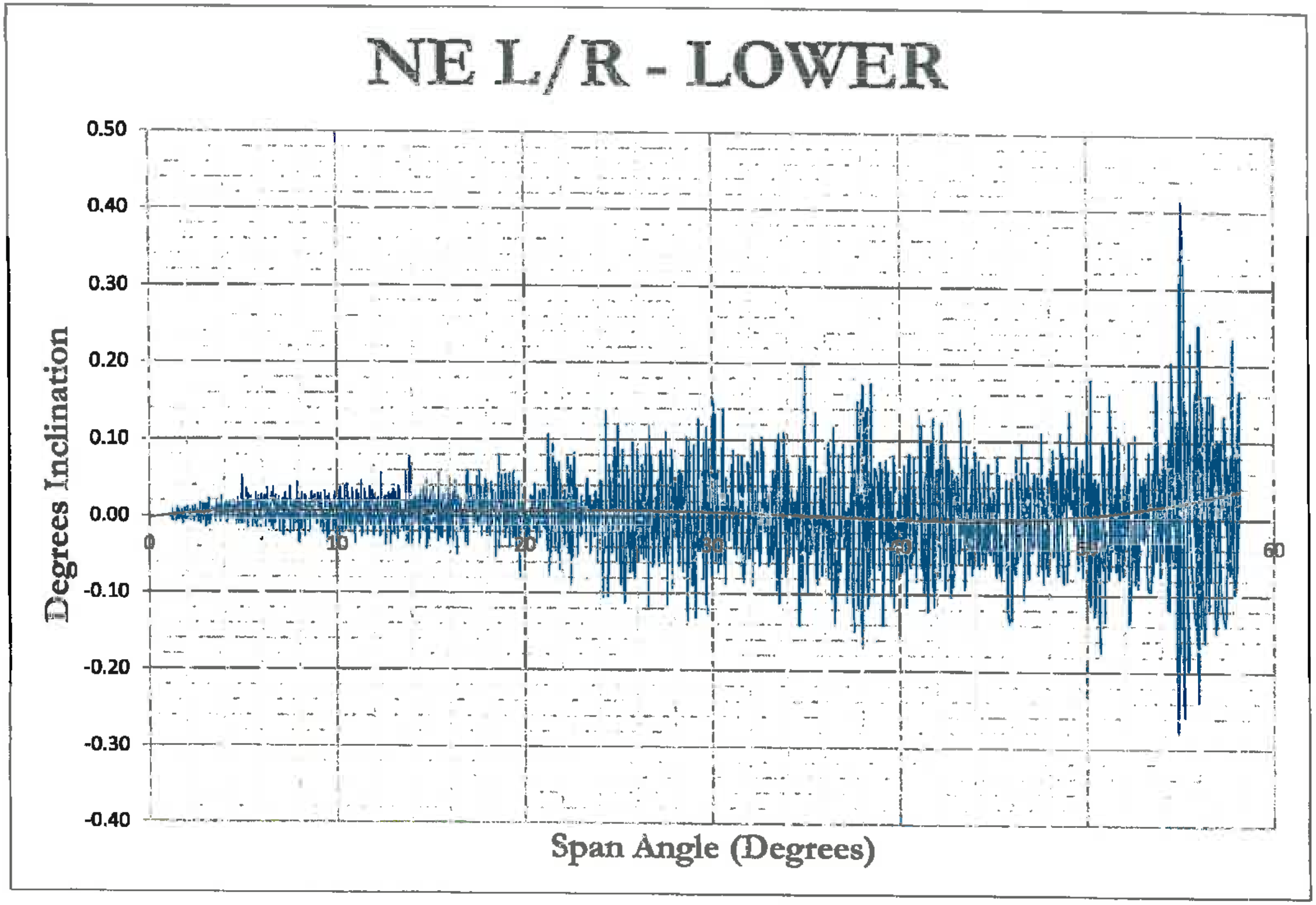
ANALOG DATA TRIAL #4



BROADWAY BRIDGE - 02720.00
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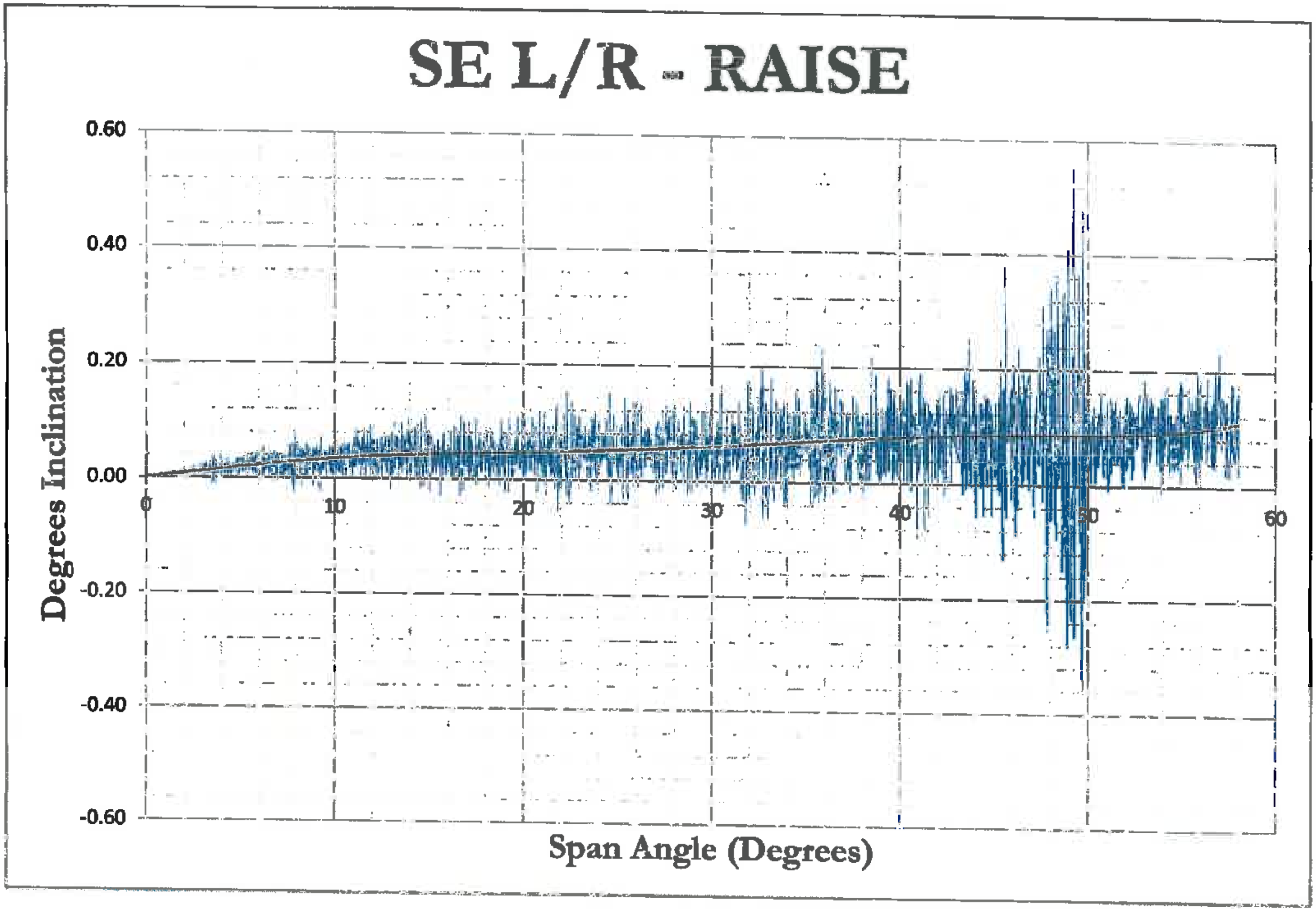
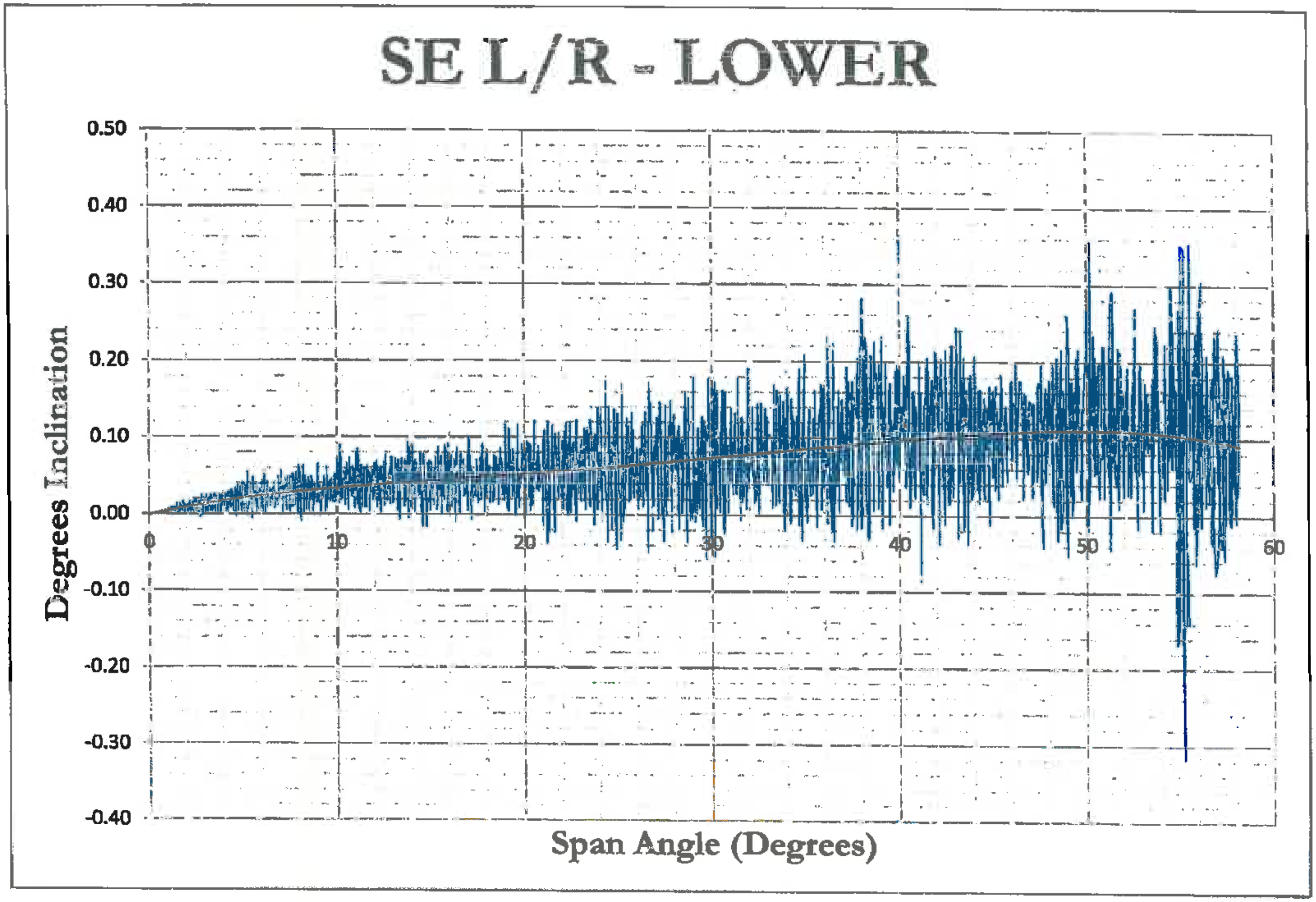
ANALOG DATA TRIAL #4



BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #4



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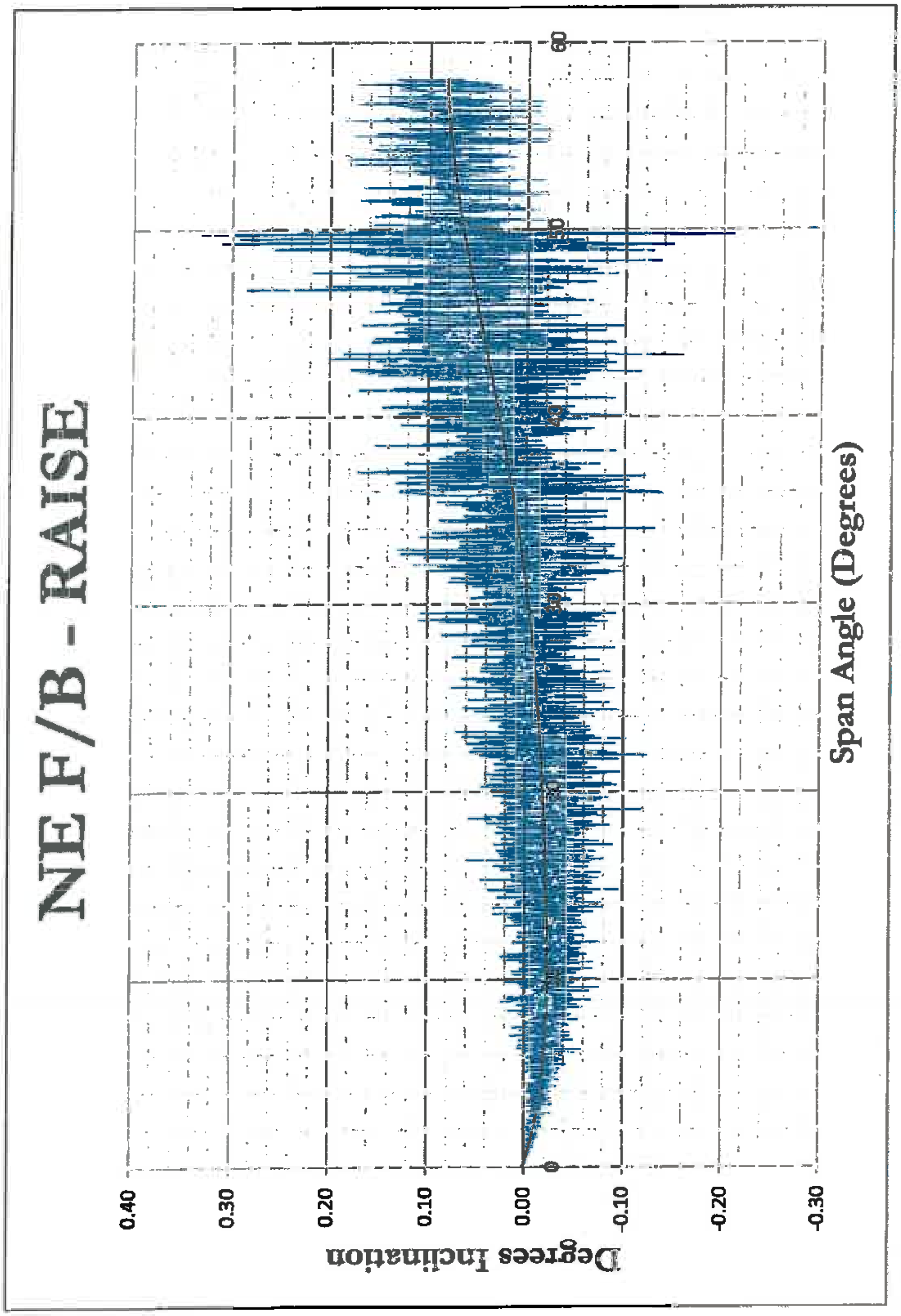

BROADWAY BRIDGE - 02720.00
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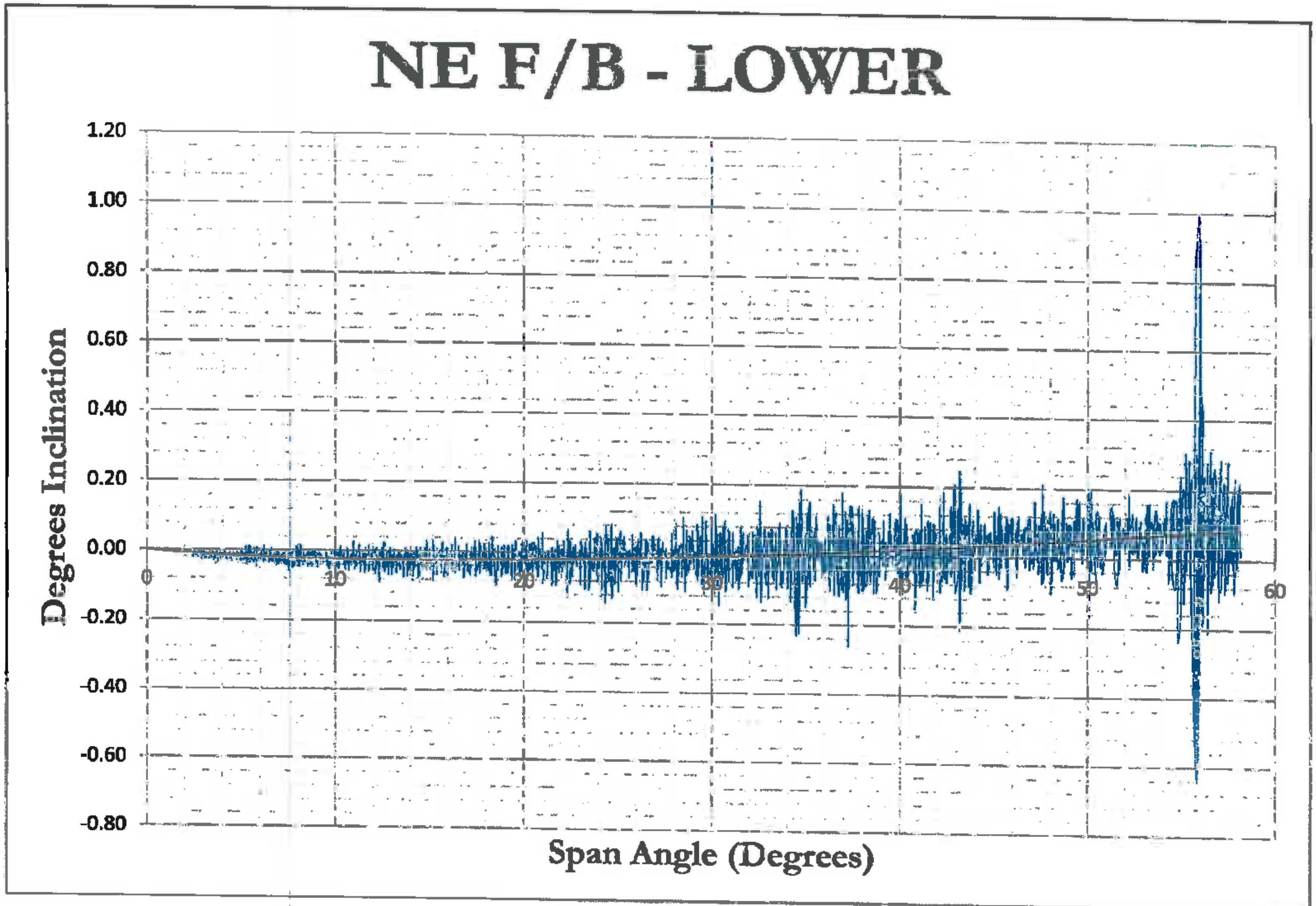
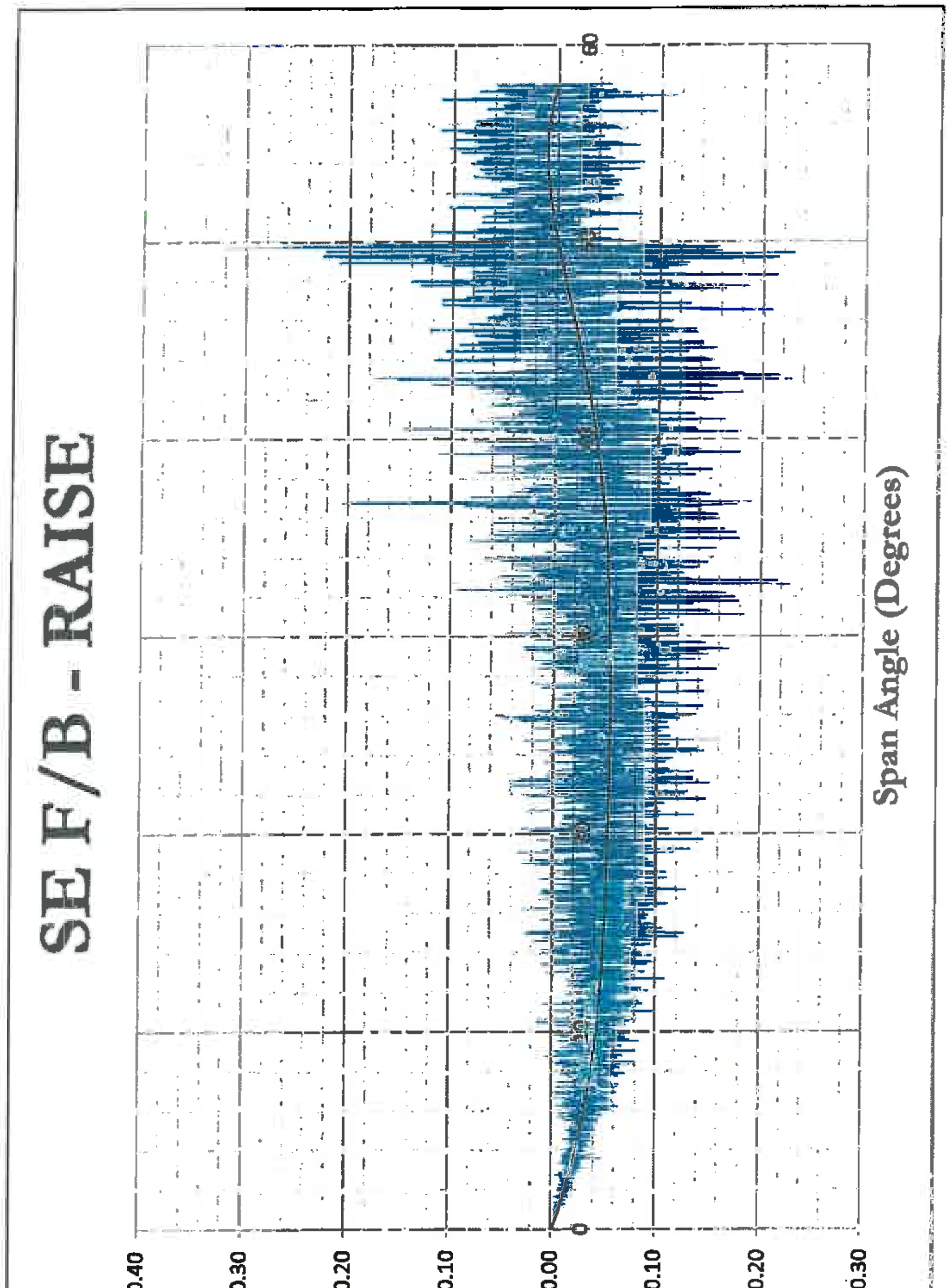


BROADWAY BRIDGE - 02720.00
EAST BRIDGE
ANALOG DATA TRIAL #4



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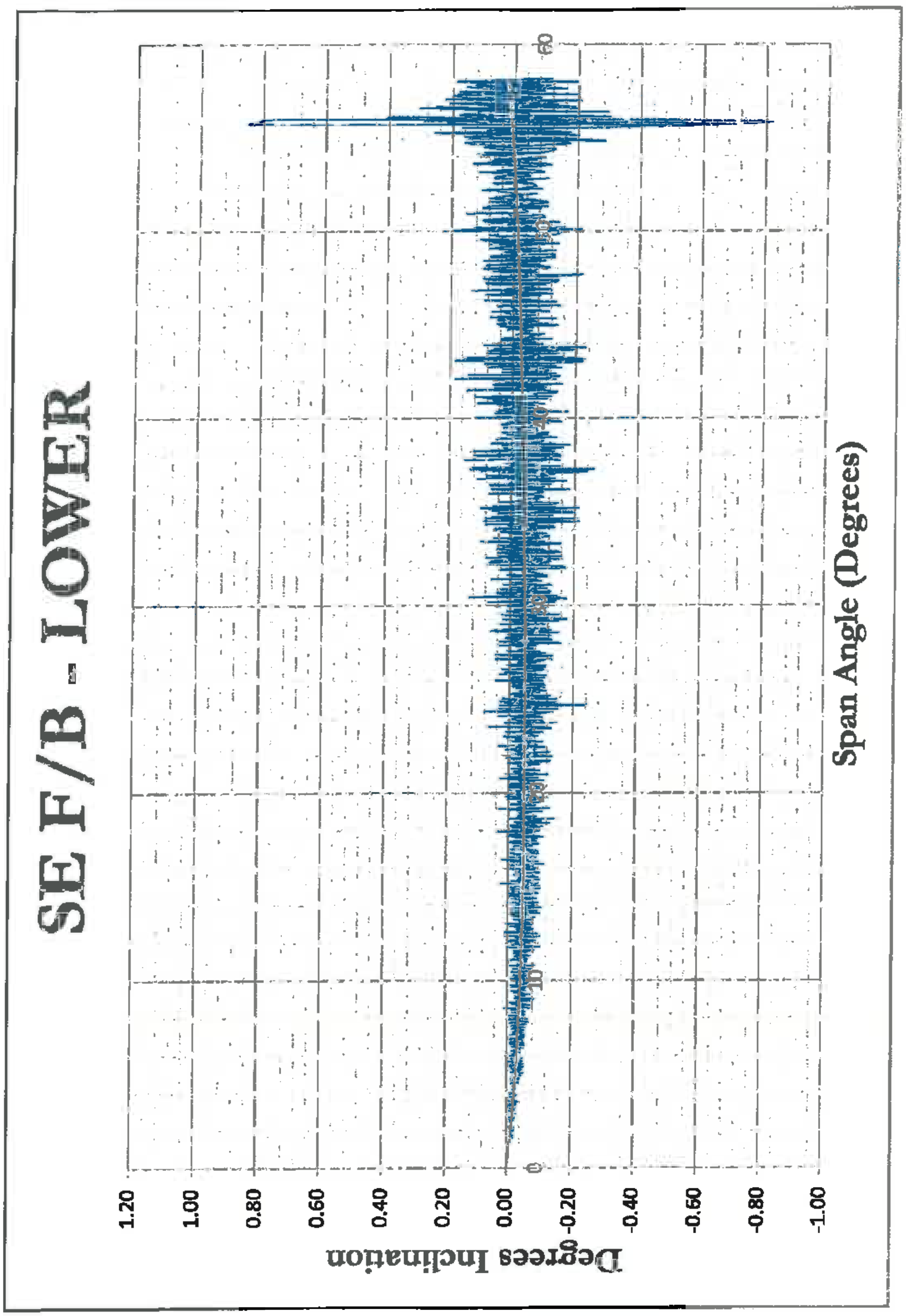
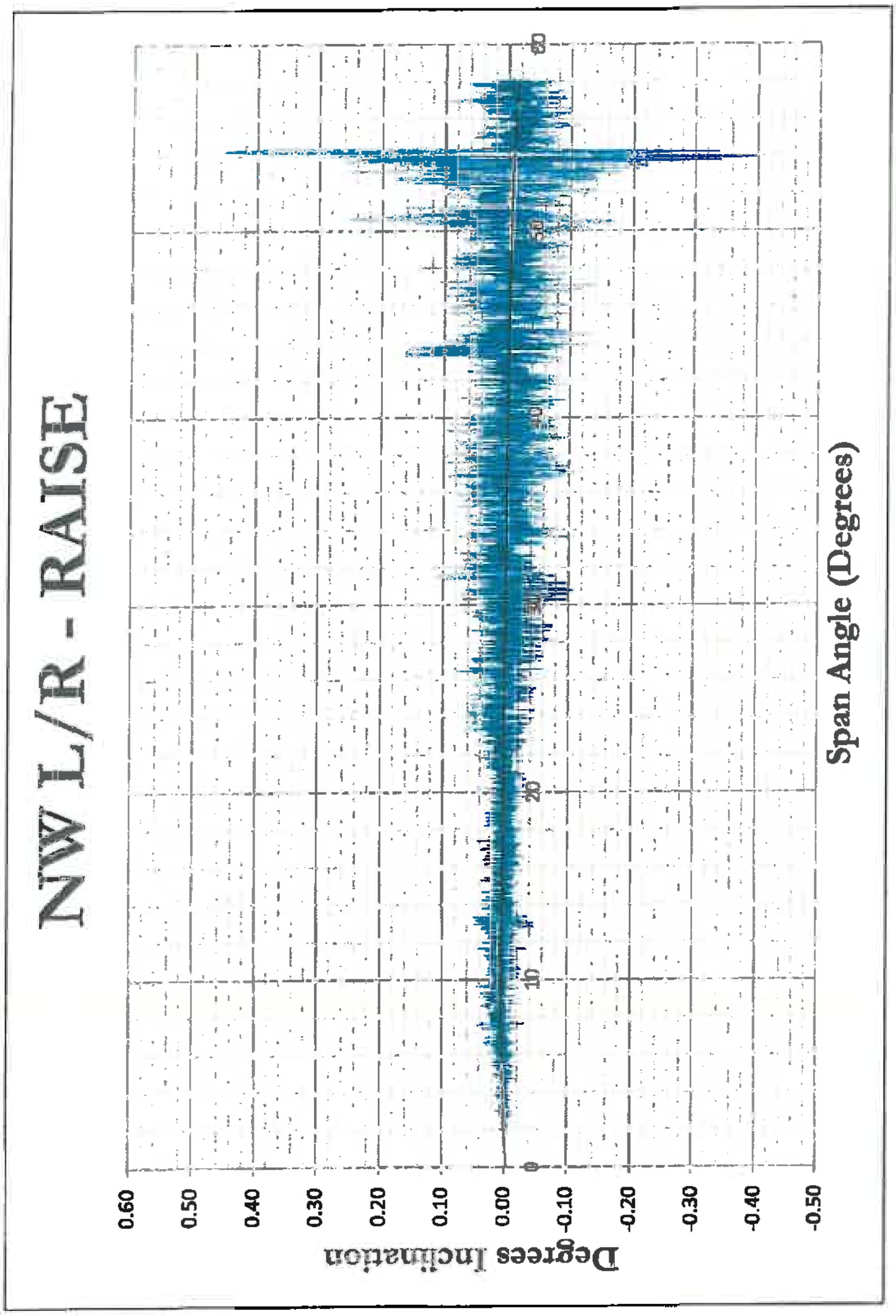
EAST BRIDGE
ANALOG DATA TRIAL #4



BROADWAY BRIDGE - 02720.00
WEST BRIDGE
ANALOG DATA TRIAL #1



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WEST BRIDGE
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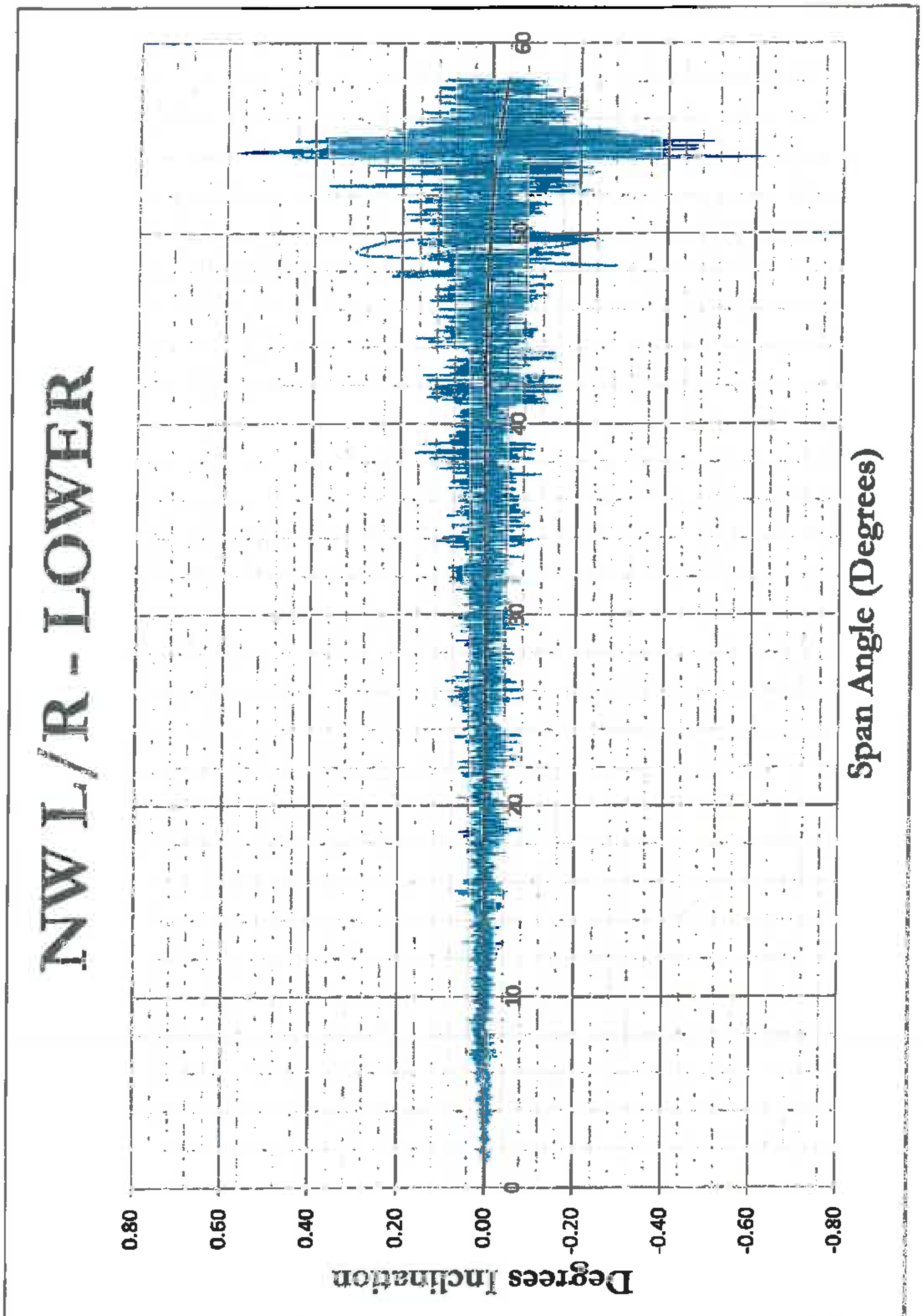

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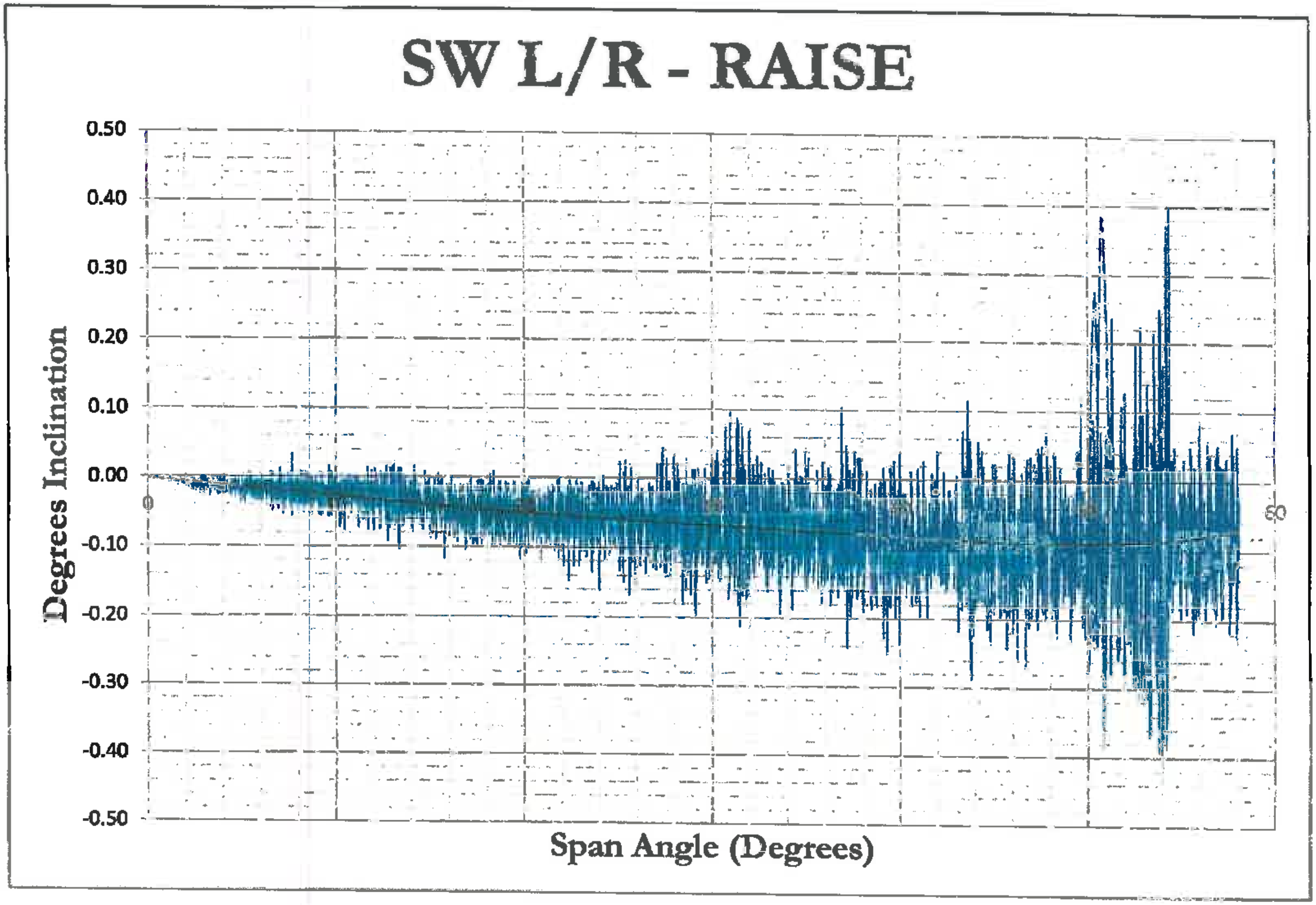
ANALOG DATA TRIAL #1



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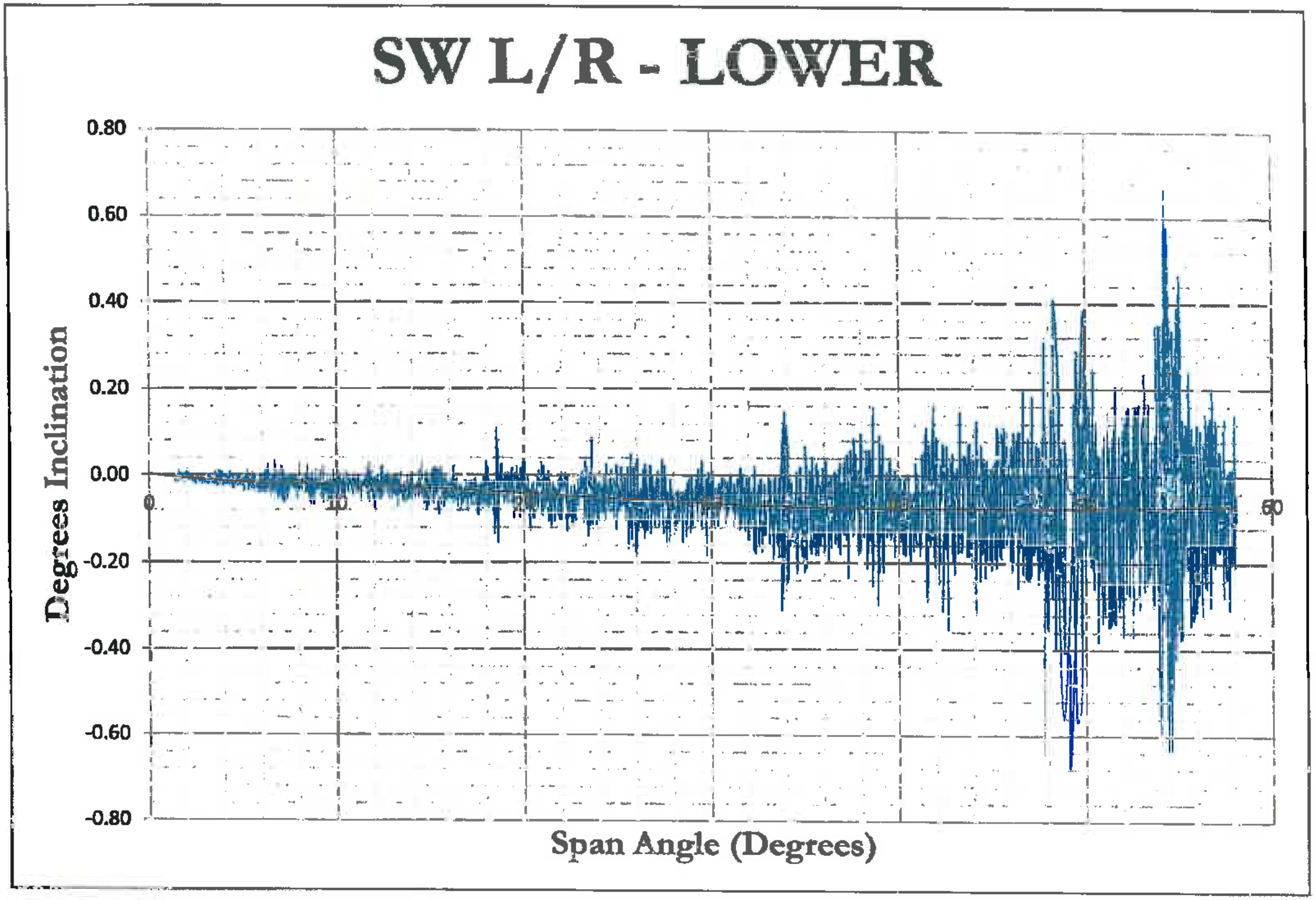

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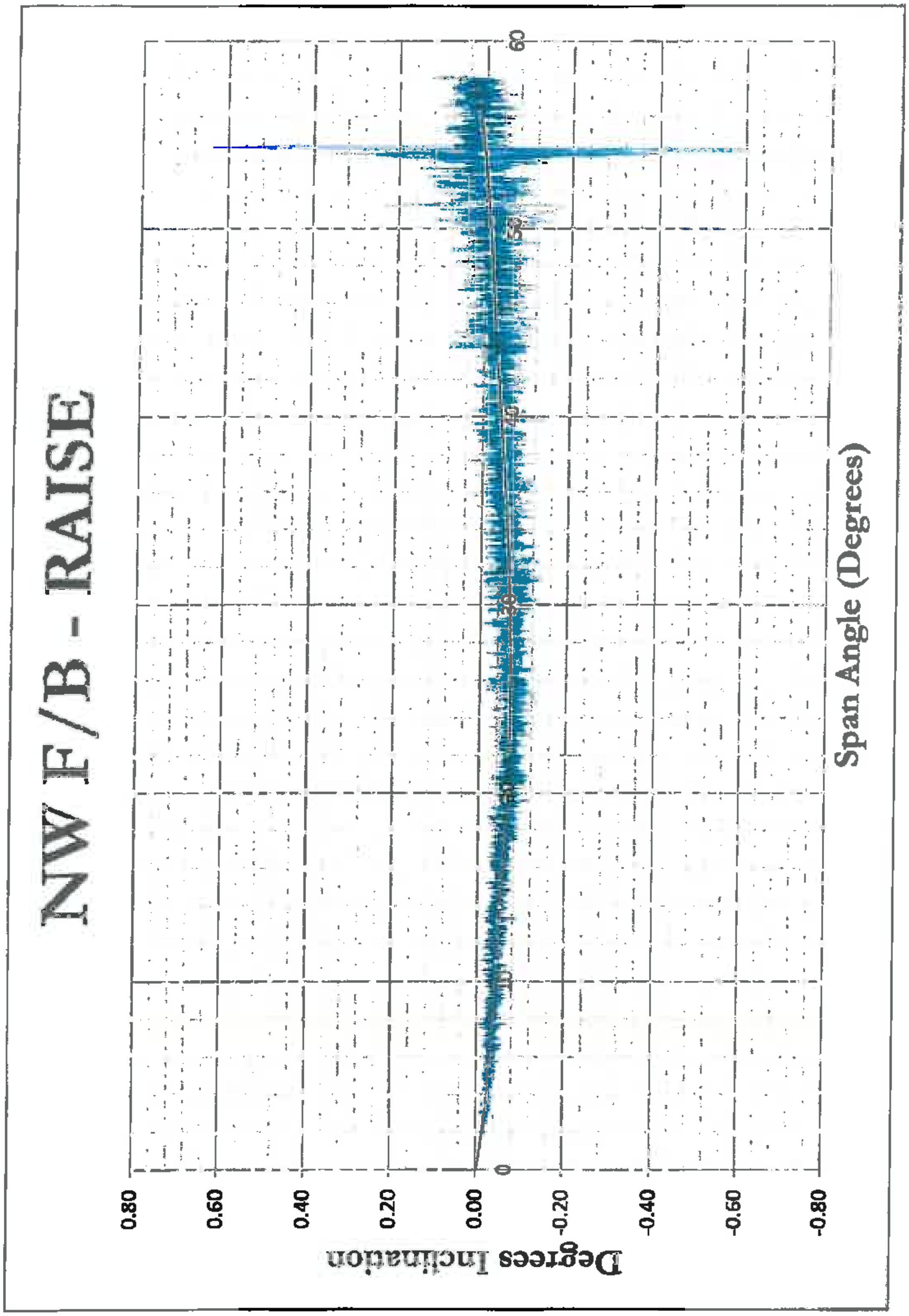

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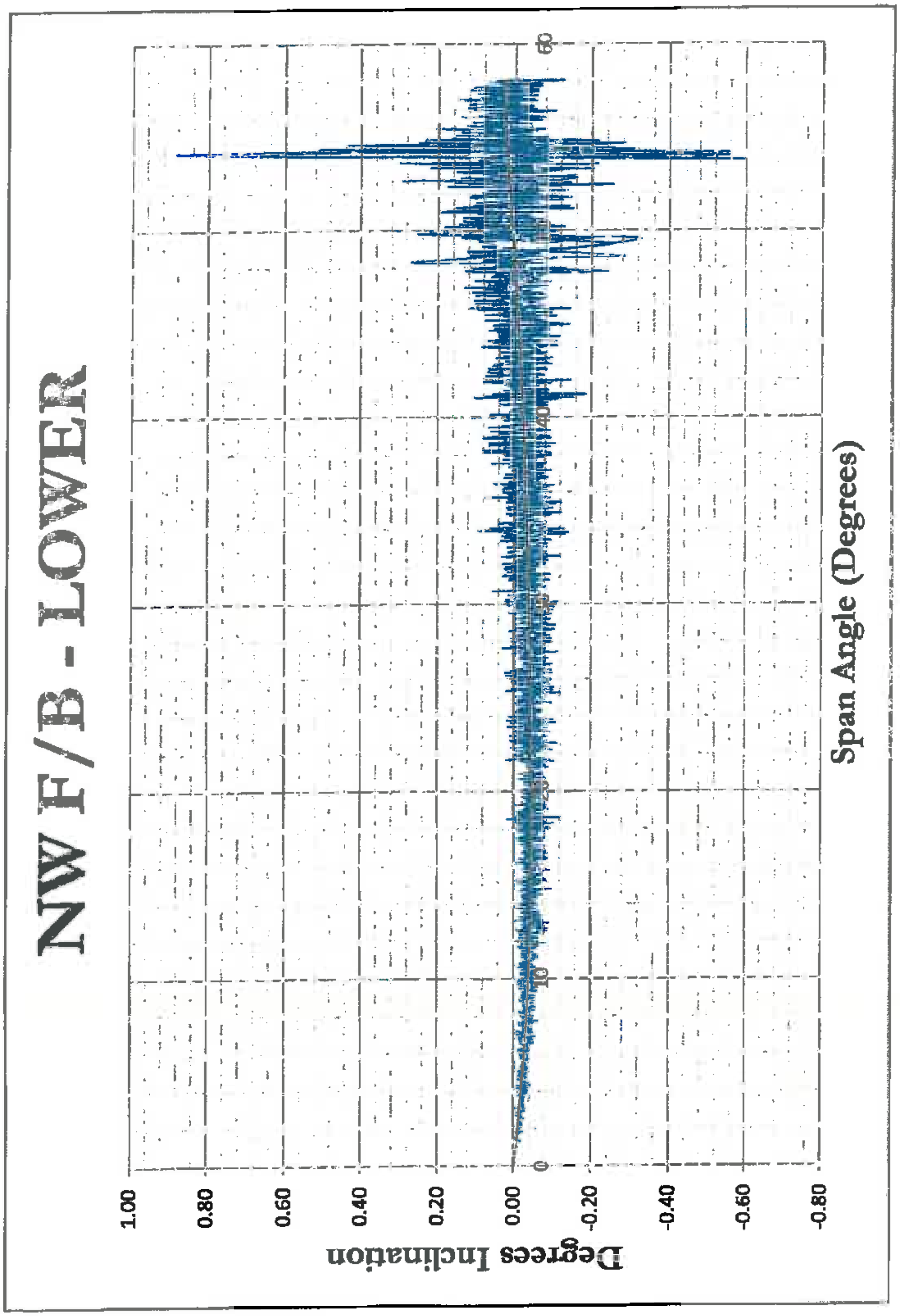

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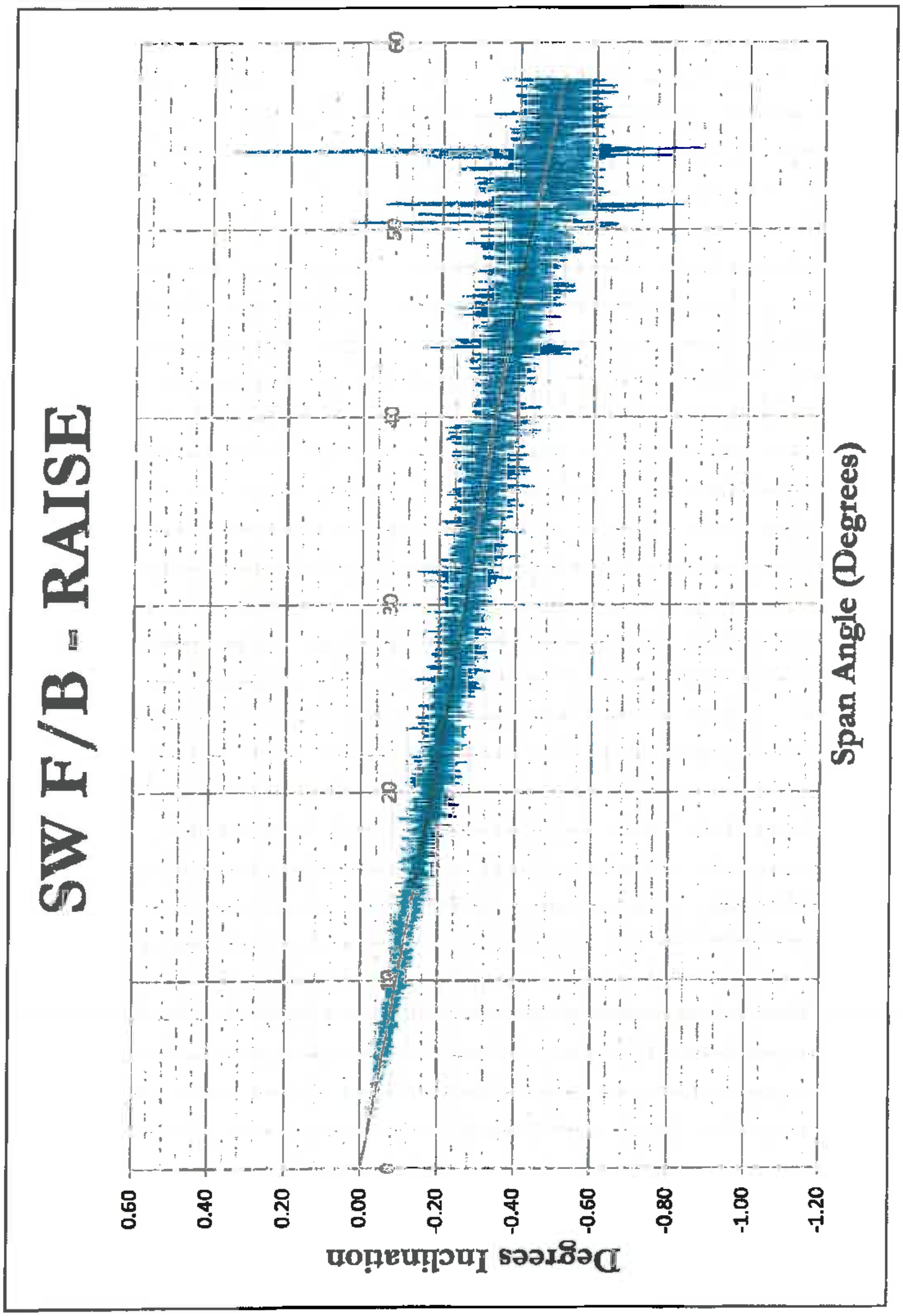
ANALOG DATA TRIAL #1



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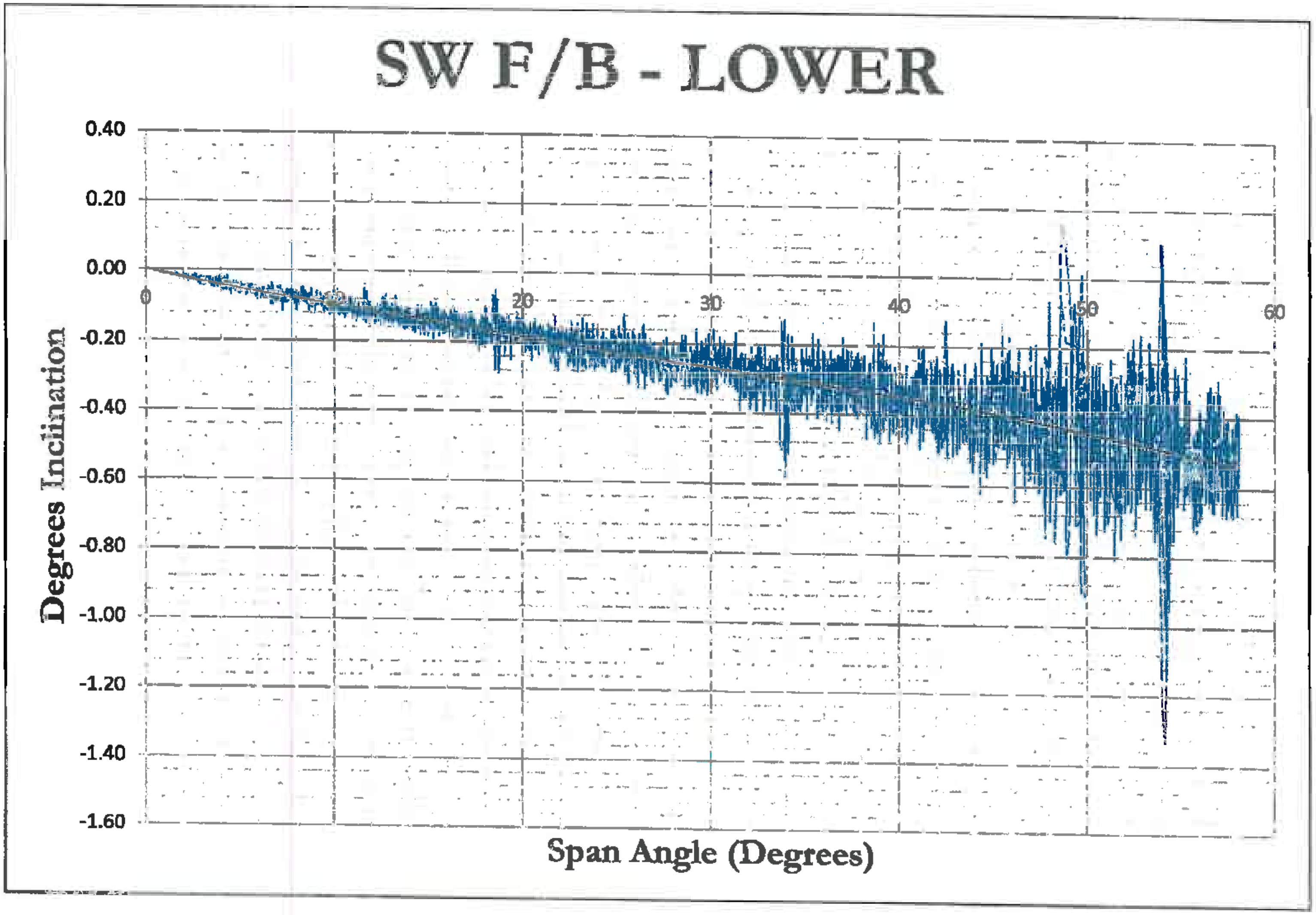
ANALOG DATA TRIAL #1



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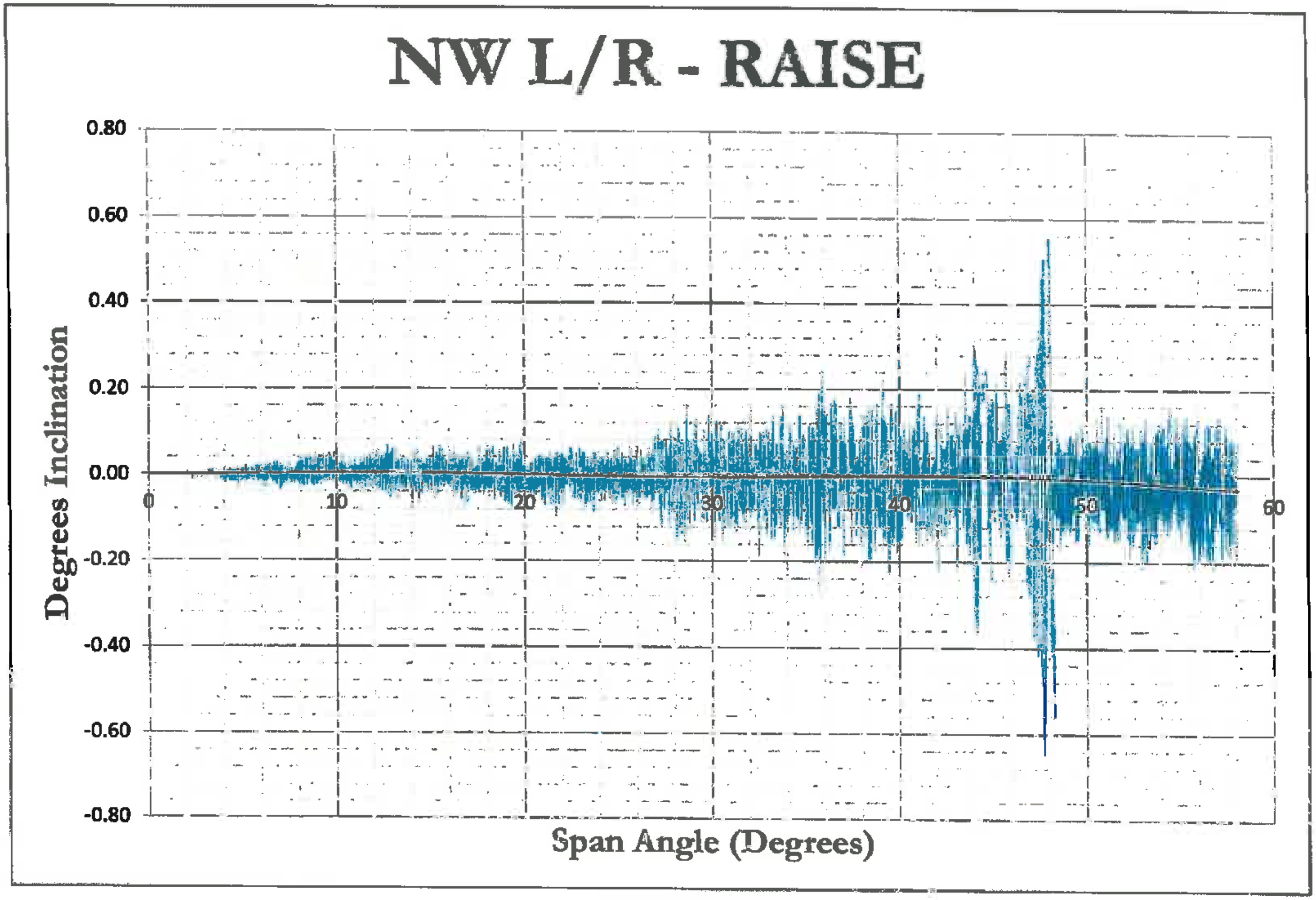
ANALOG DATA TRIAL #2



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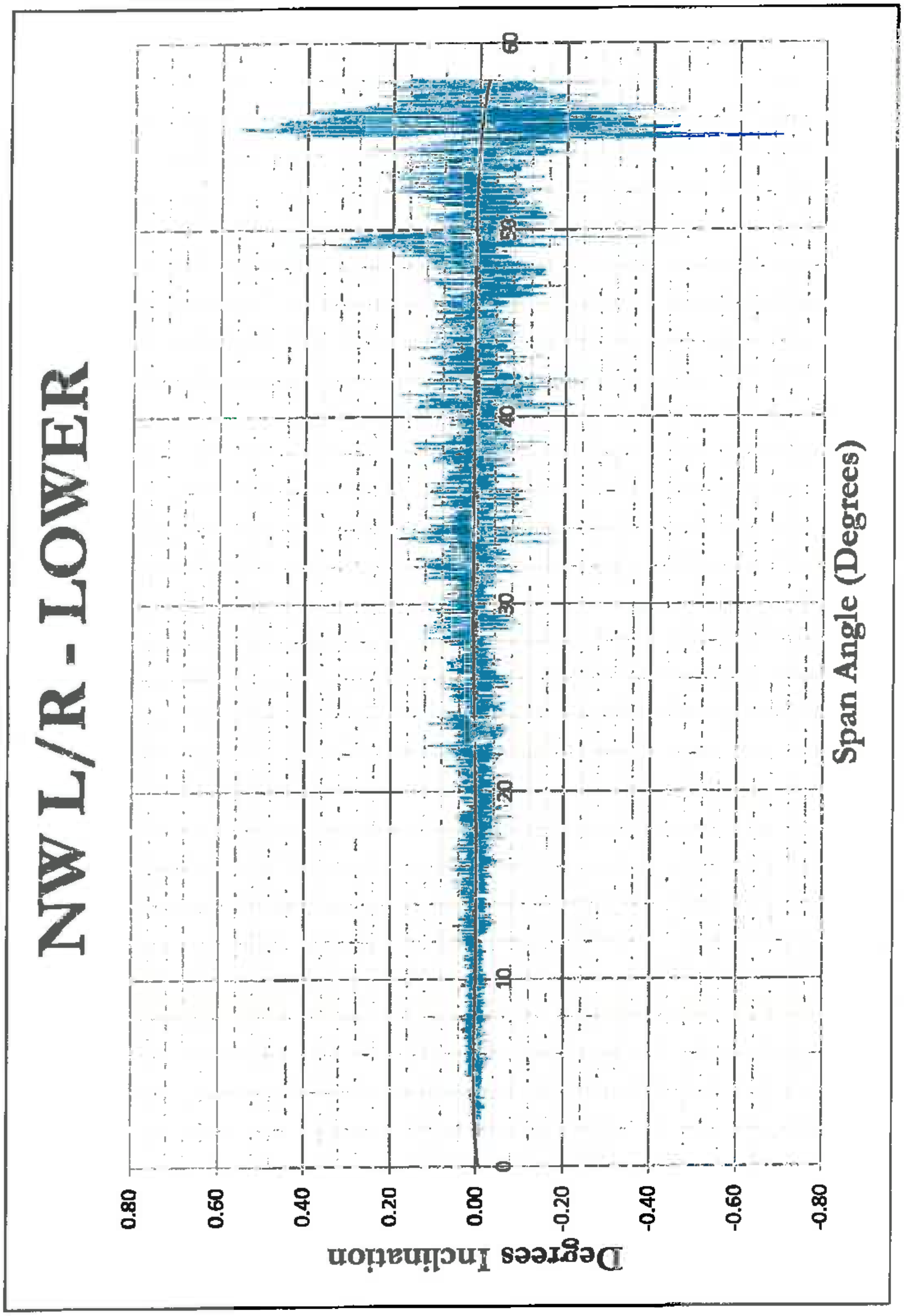

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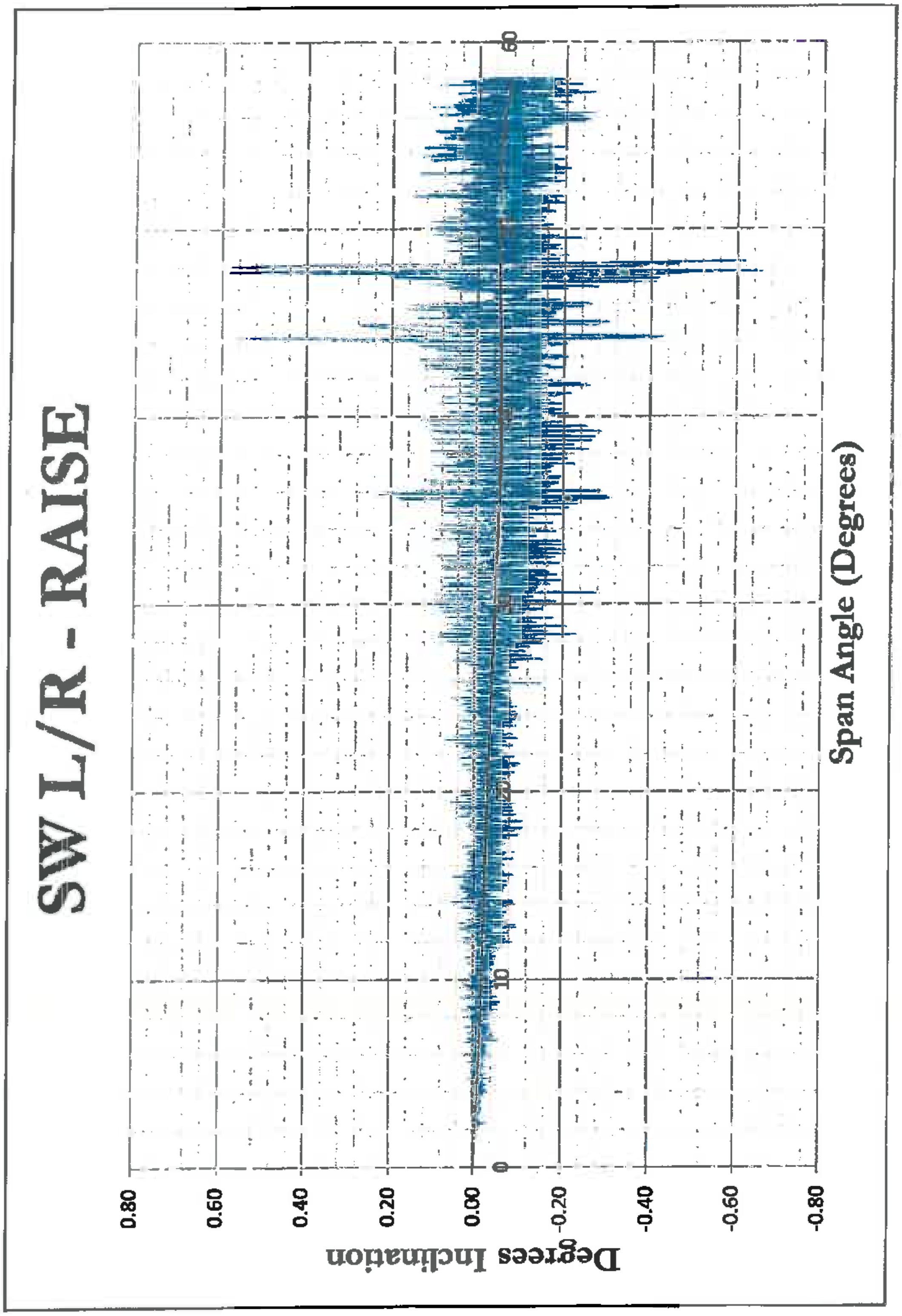

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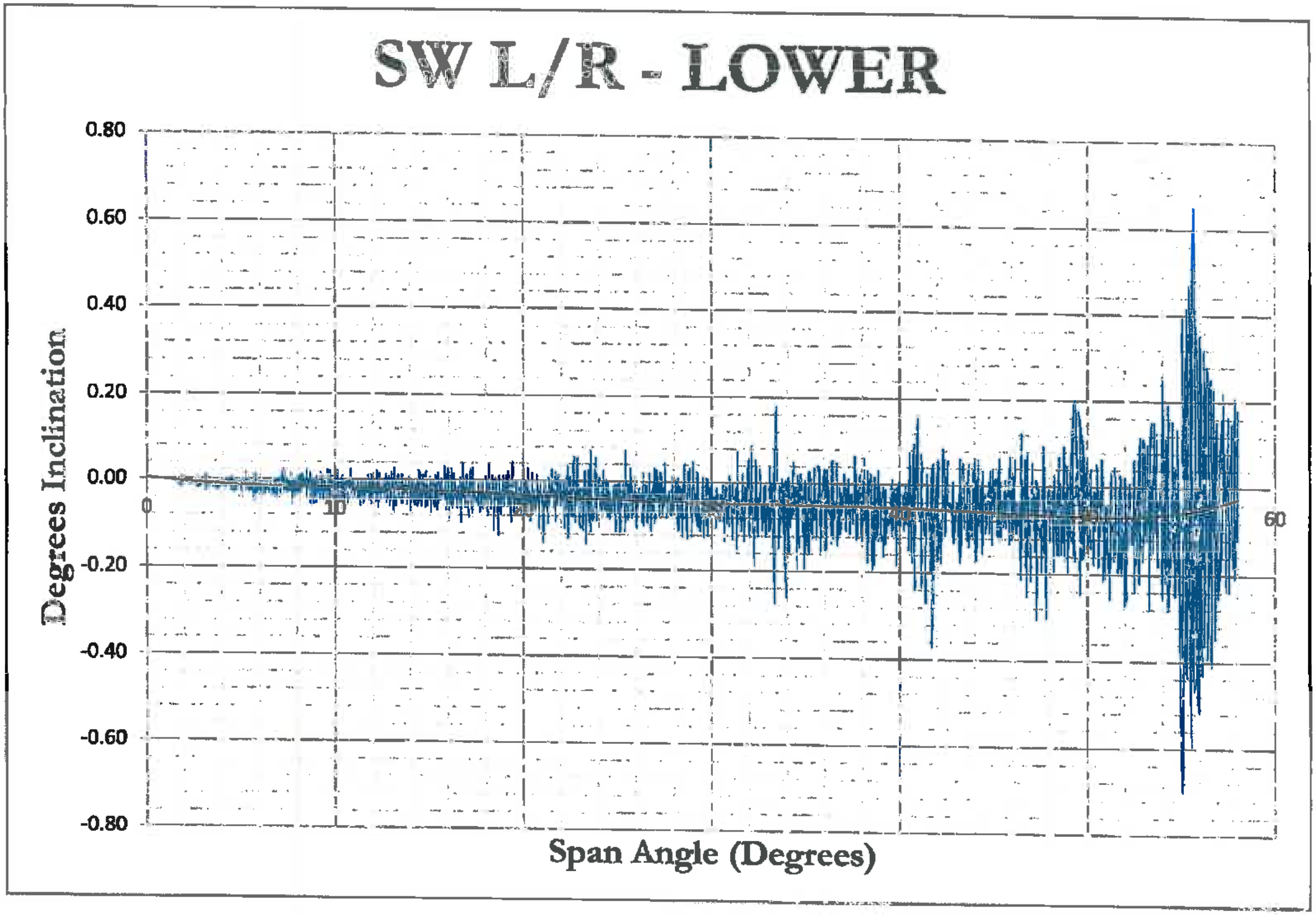
ANALOG DATA TRIAL #2



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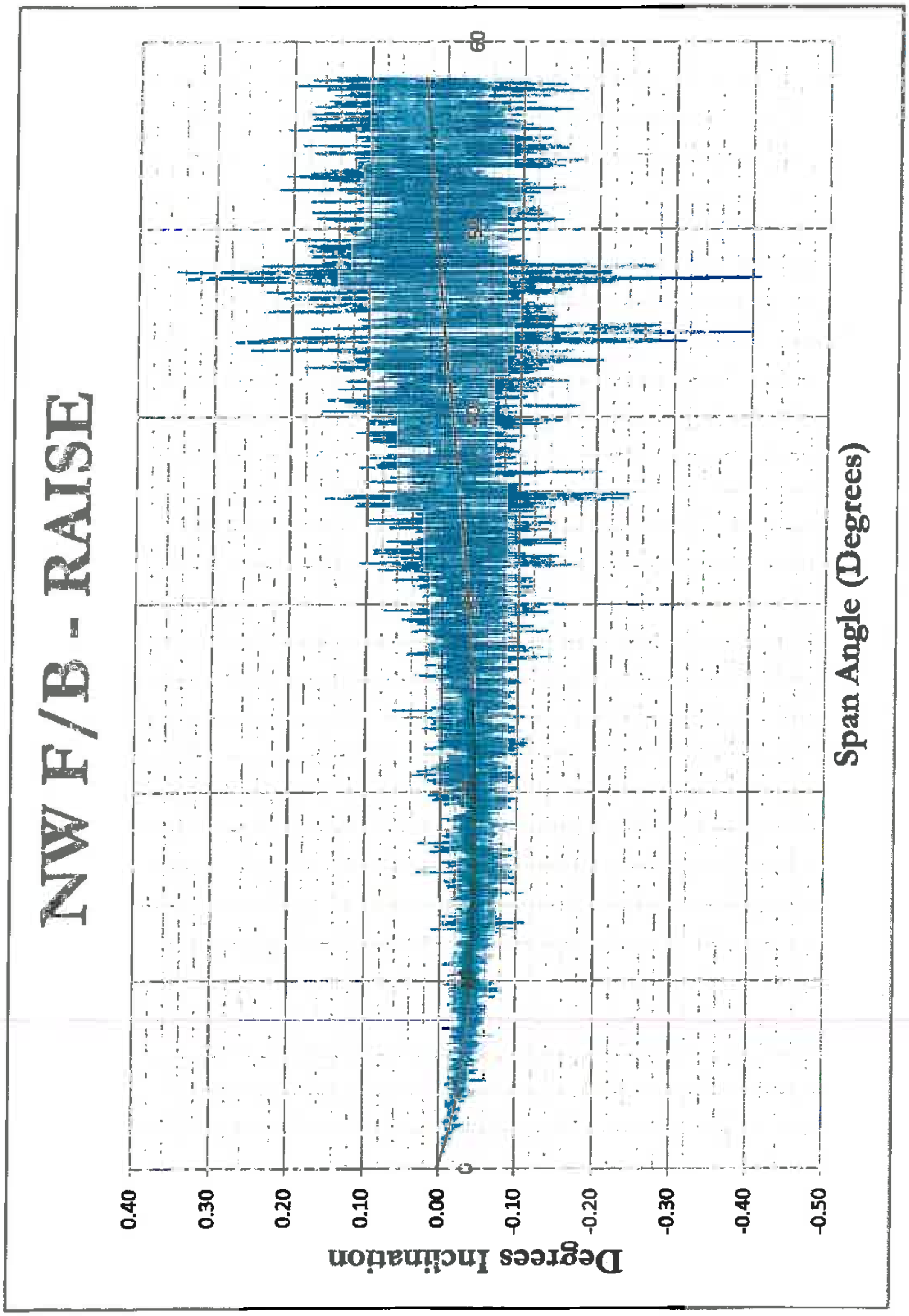

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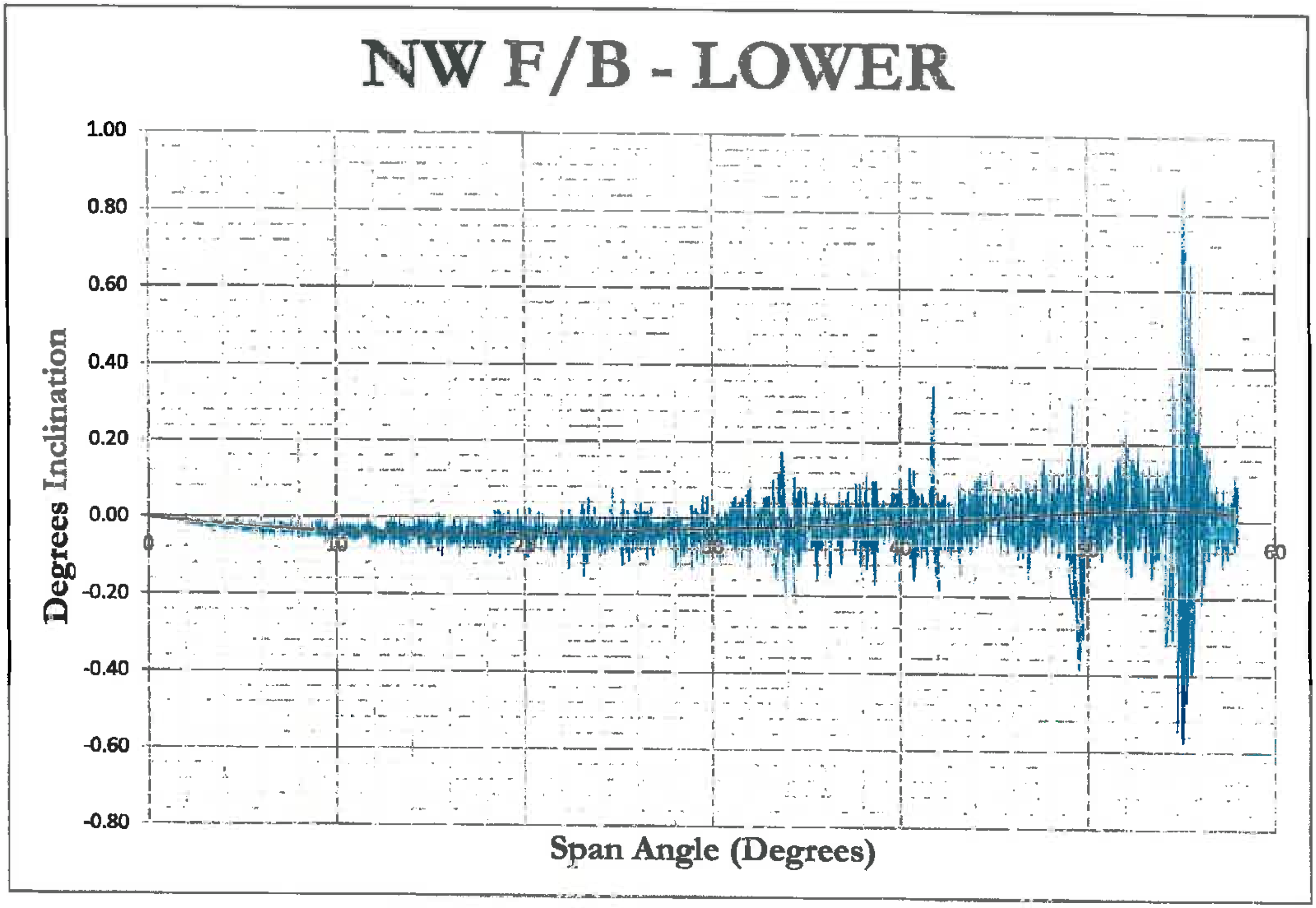

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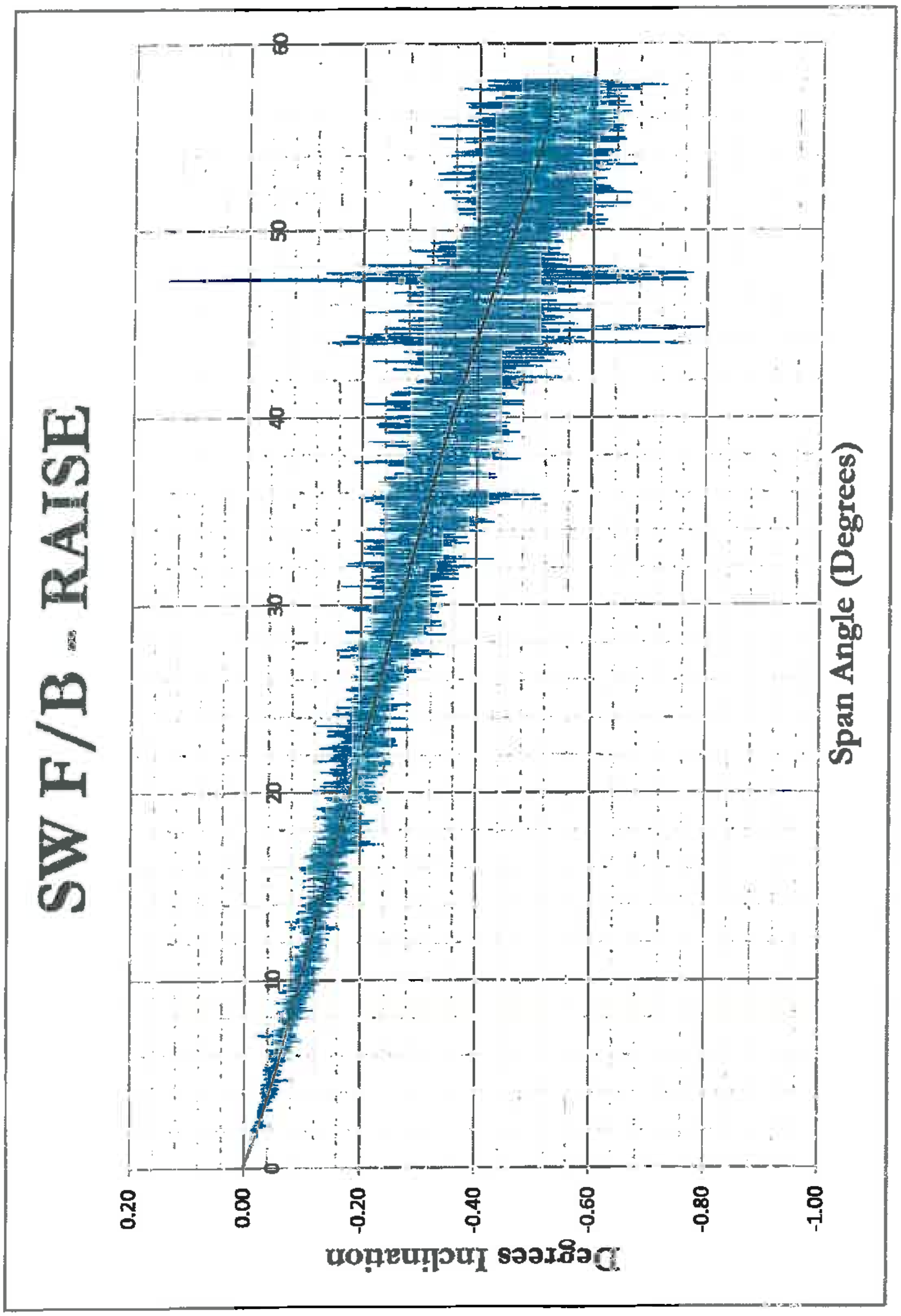
ANALOG DATA TRIAL #2



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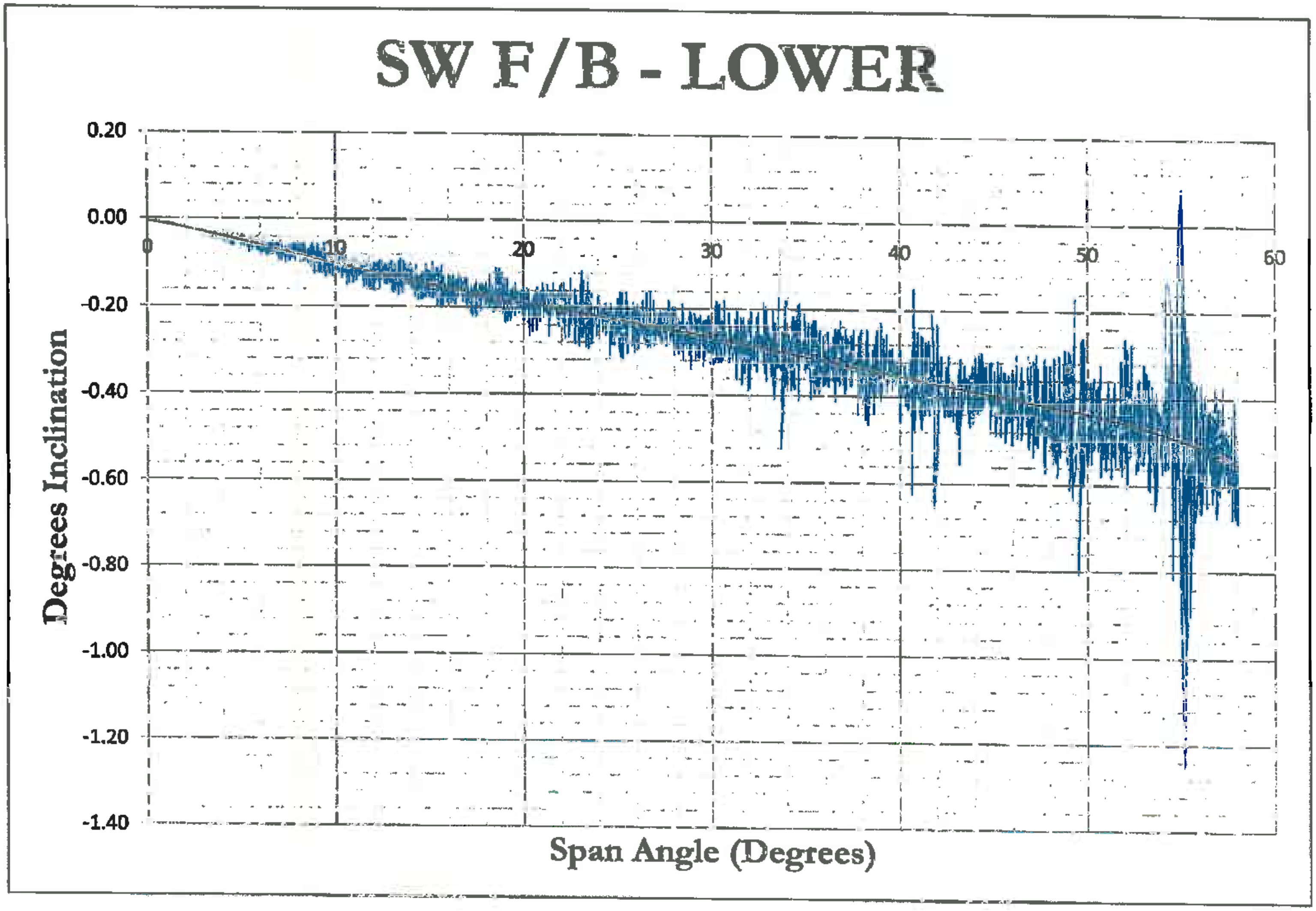
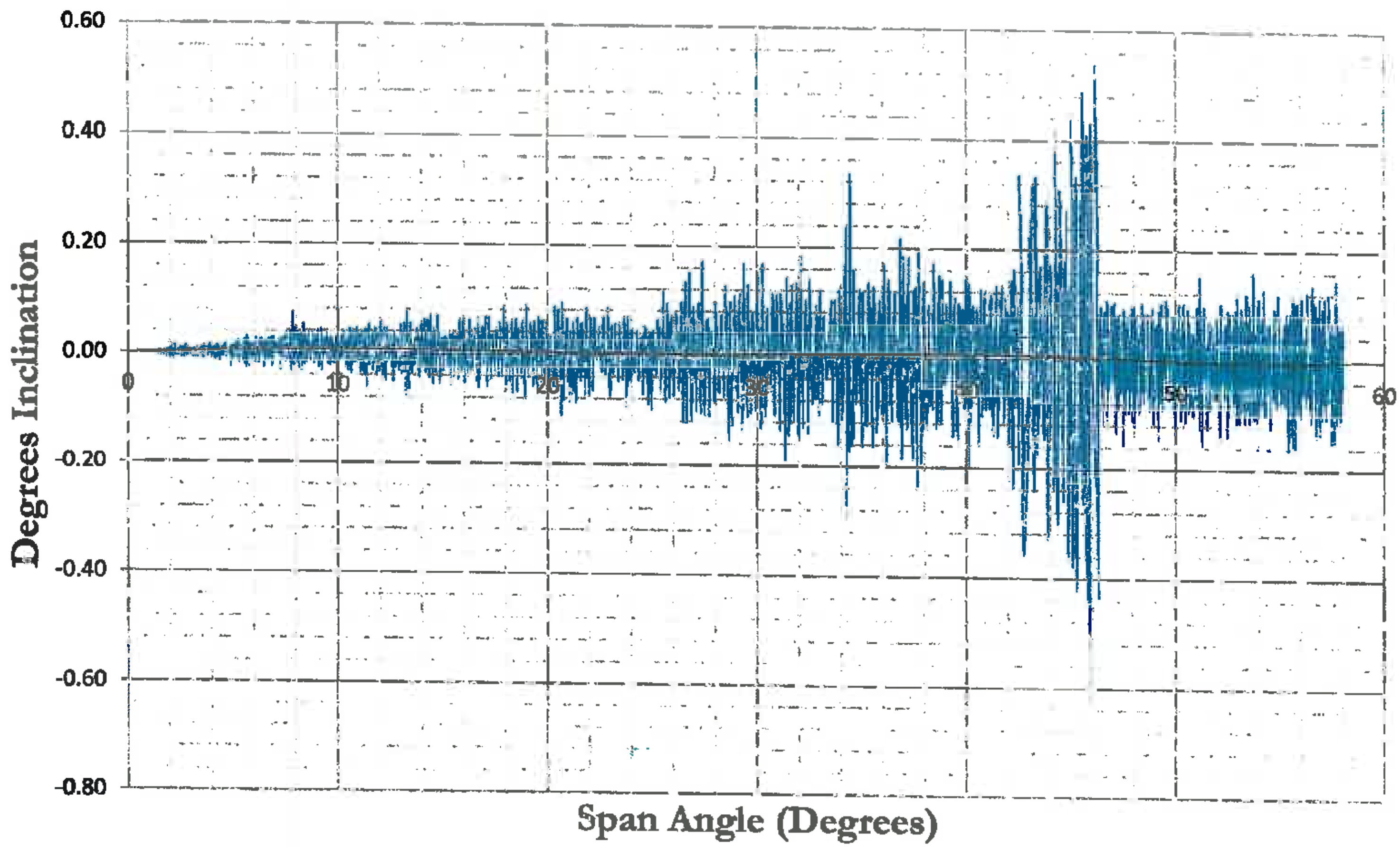
WEST BRIDGE
ANALOG DATA TRIAL #2



BROADWAY BRIDGE - 02720.00
WEST BRIDGE
ANALOG DATA TRIAL #3

NW L/R - RAISE



BROADWAY BRIDGE - 02720.00
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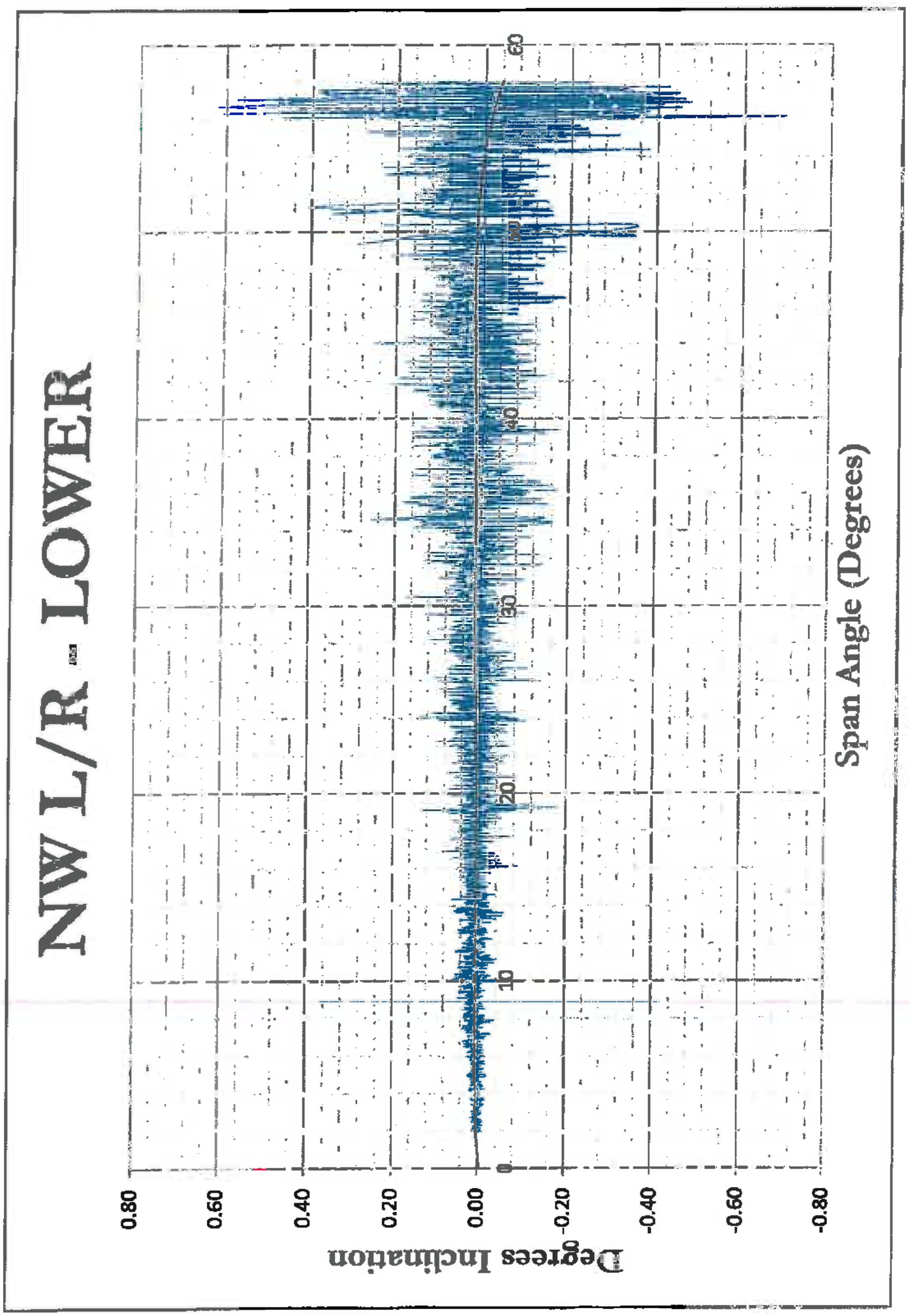
ANALOG DATA TRIAL #3



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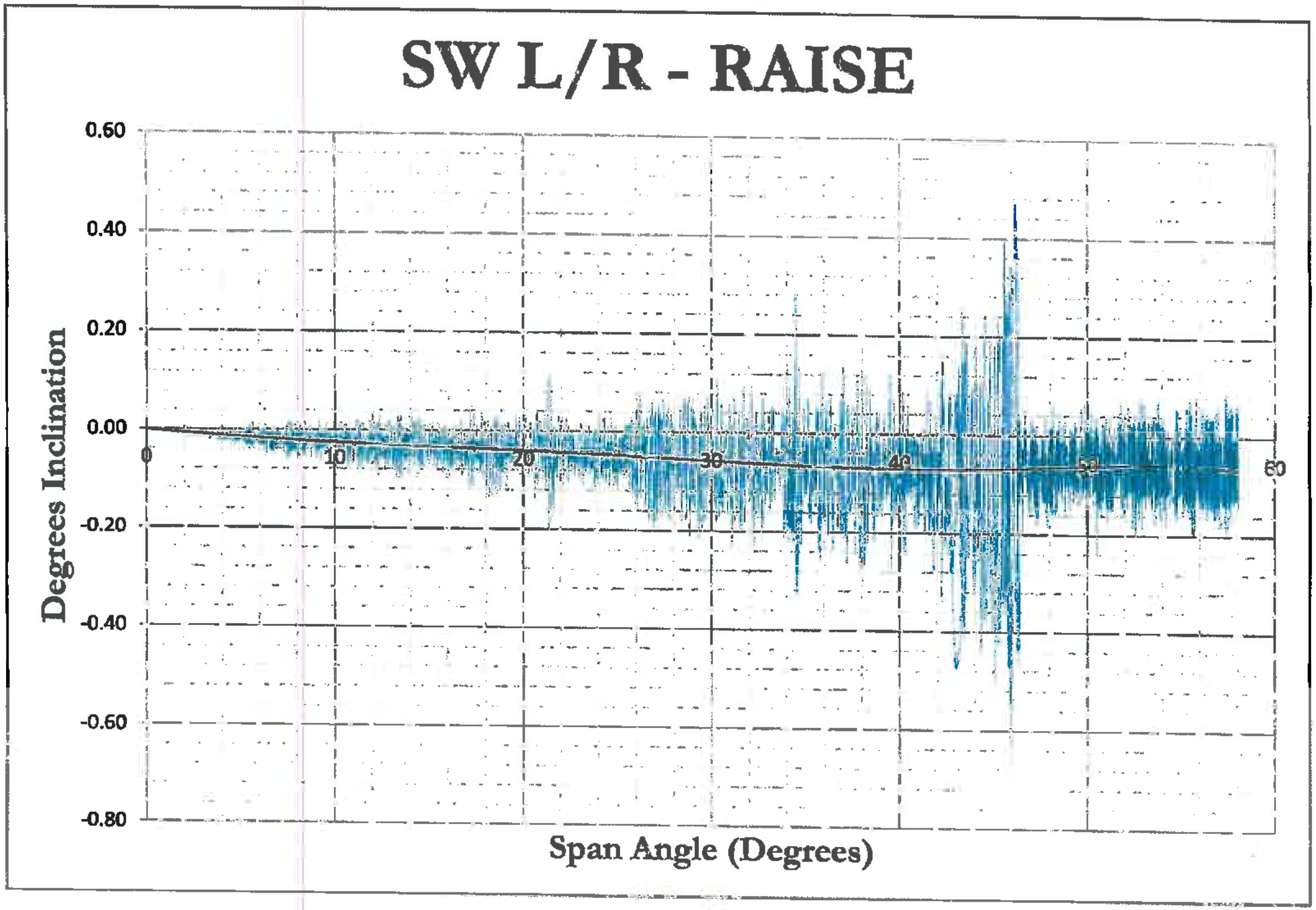
WEST BRIDGE
ANALOG DATA TRIAL #3



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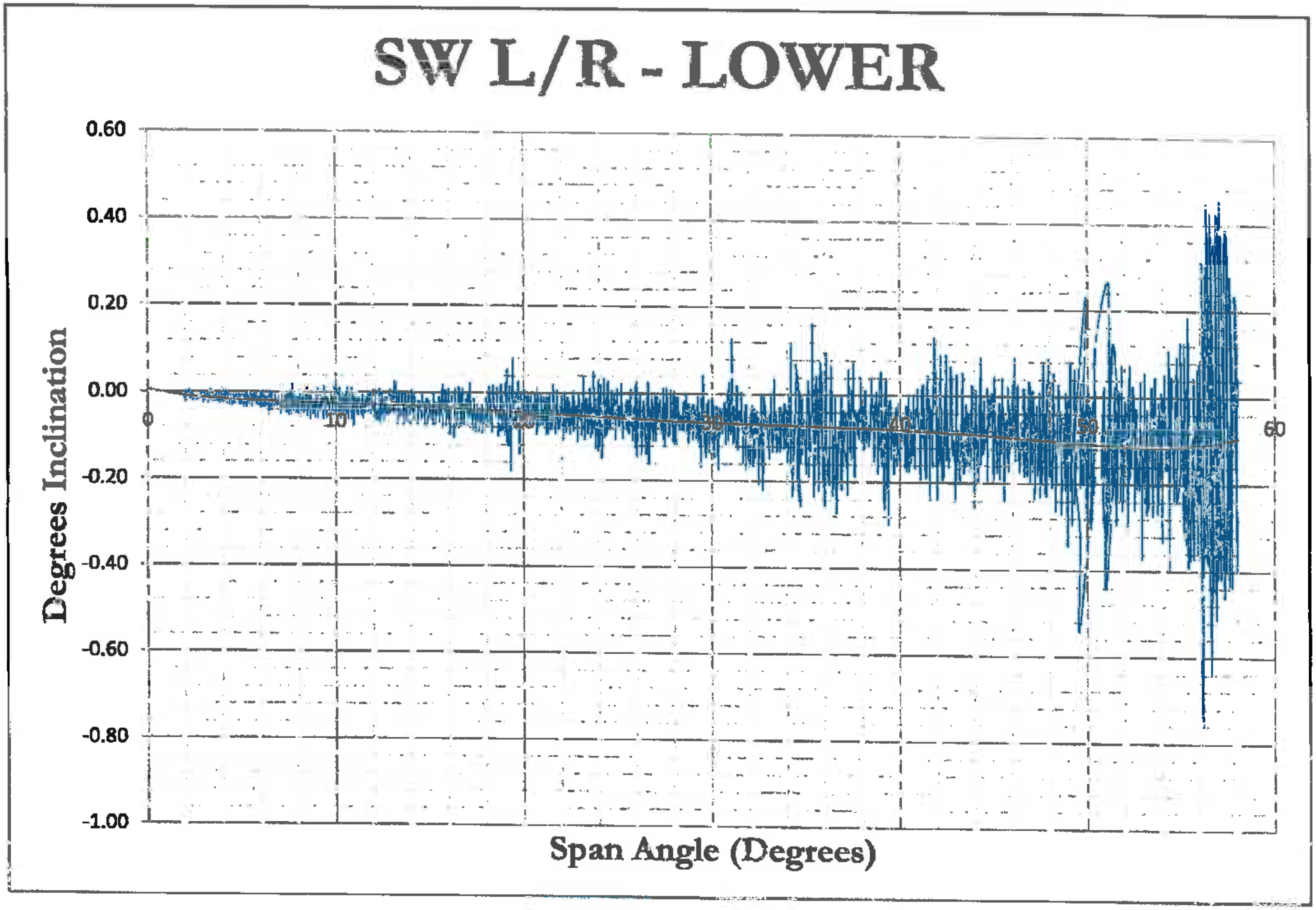
ANALOG DATA TRIAL #3



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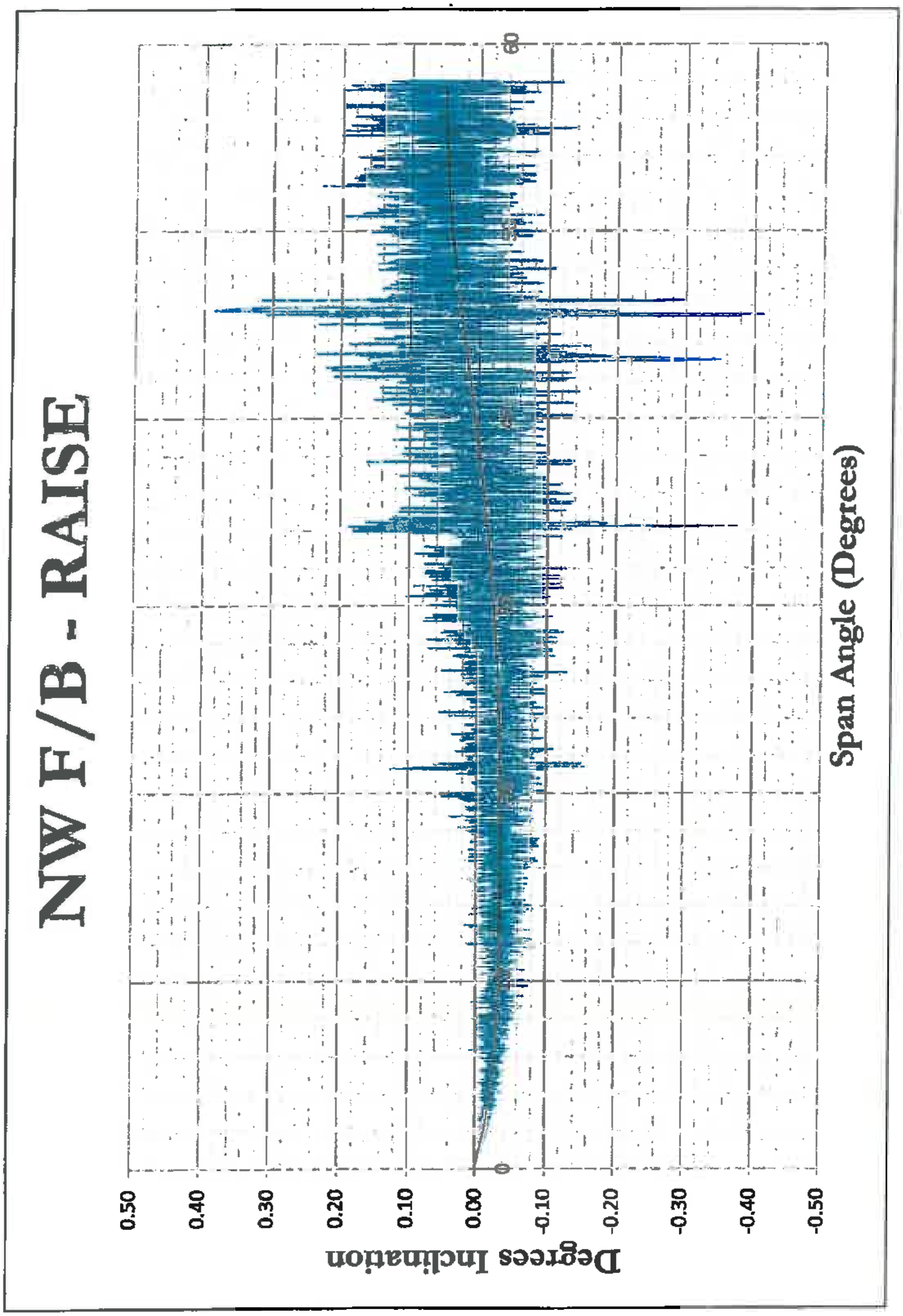

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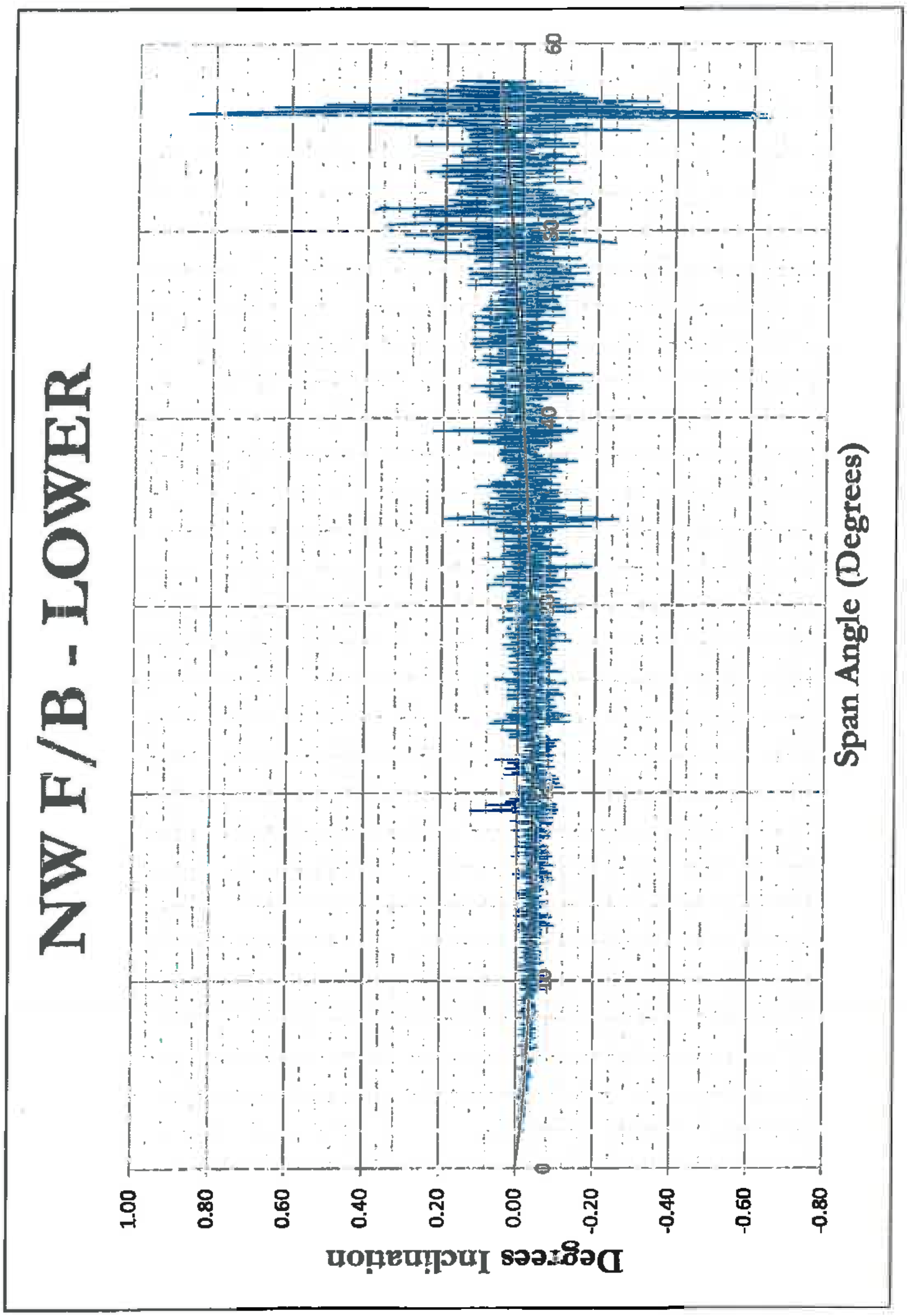
ANALOG DATA TRIAL #3



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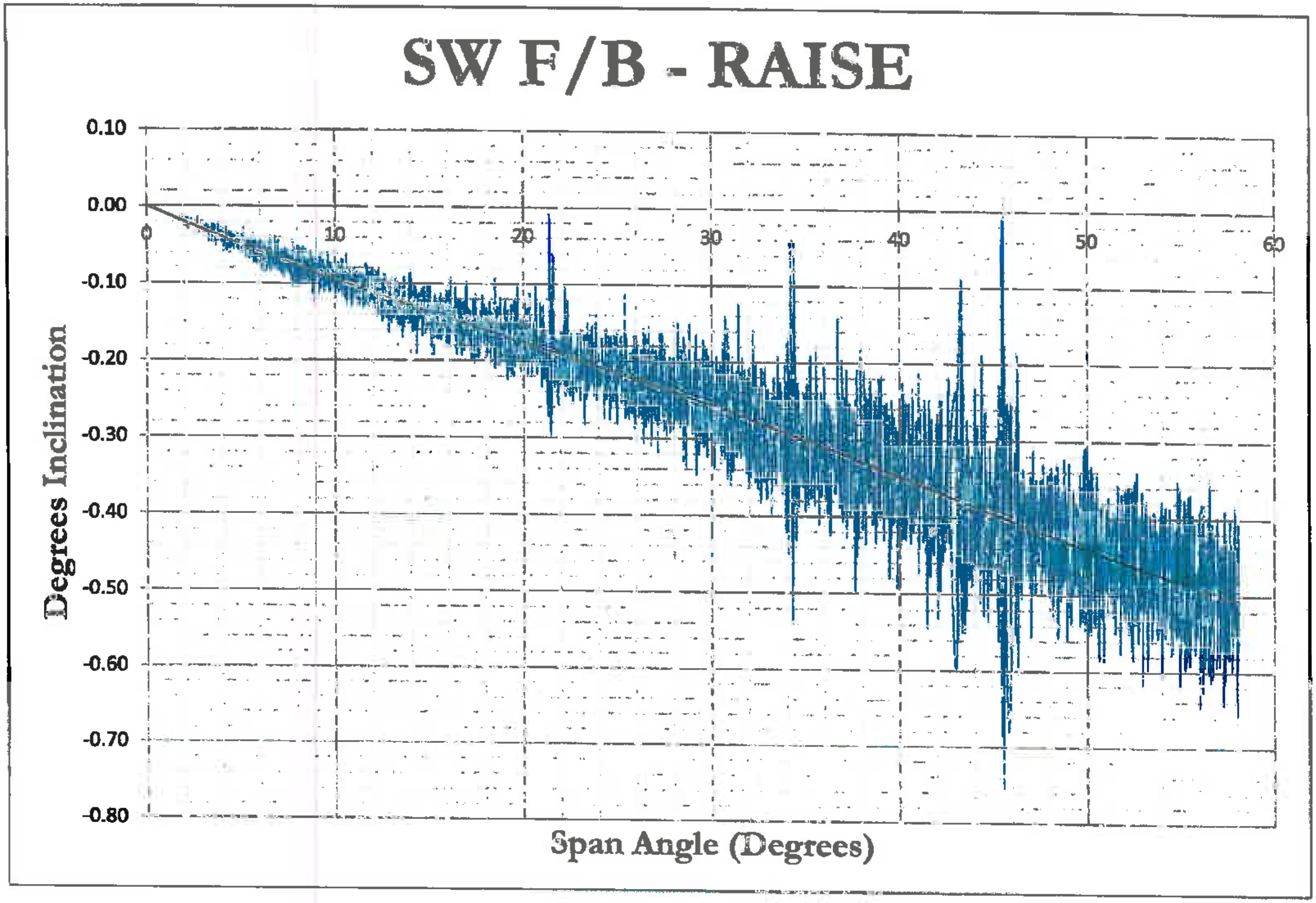
WEST BRIDGE
ANALOG DATA TRIAL #3



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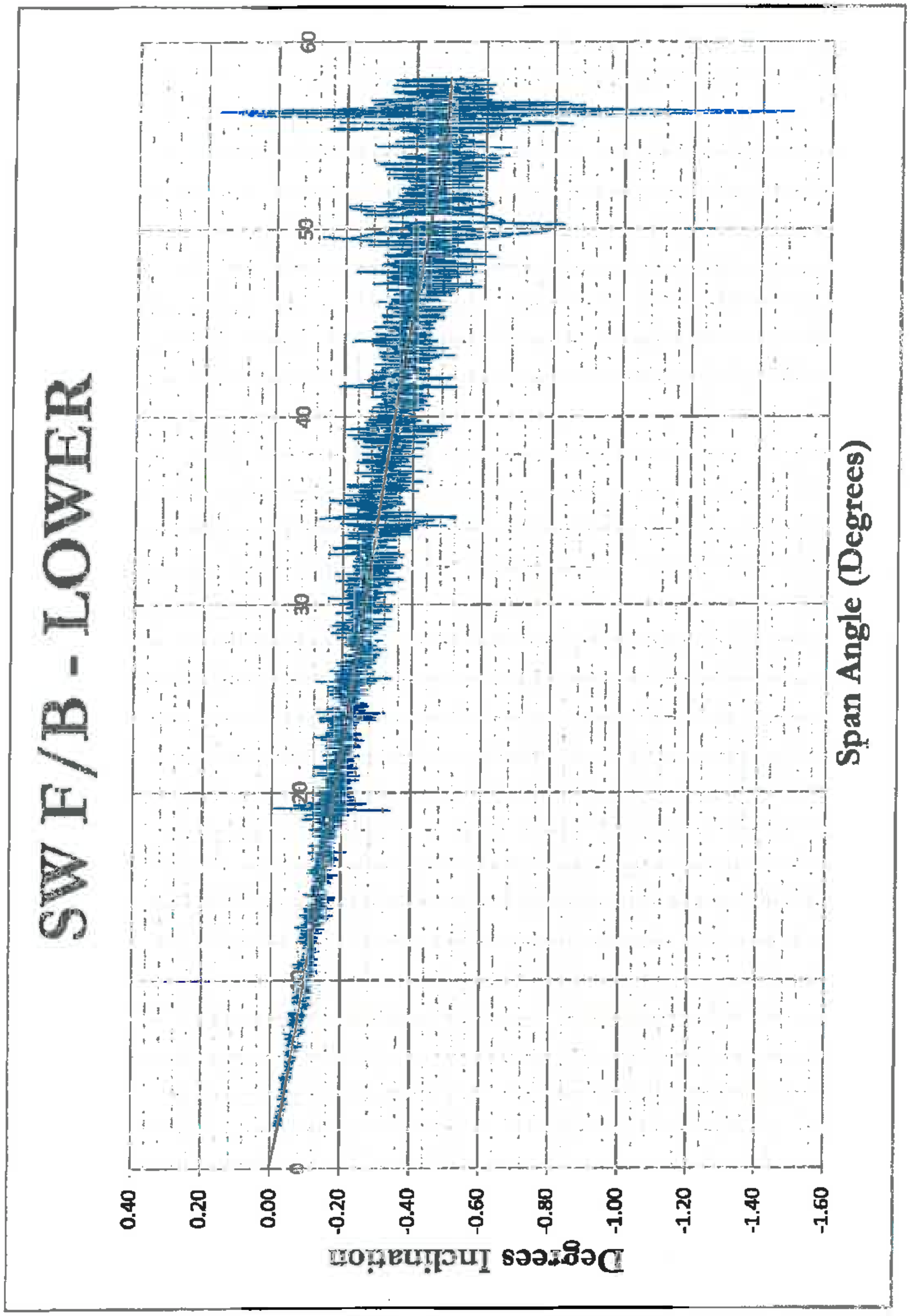
ANALOG DATA TRIAL #3



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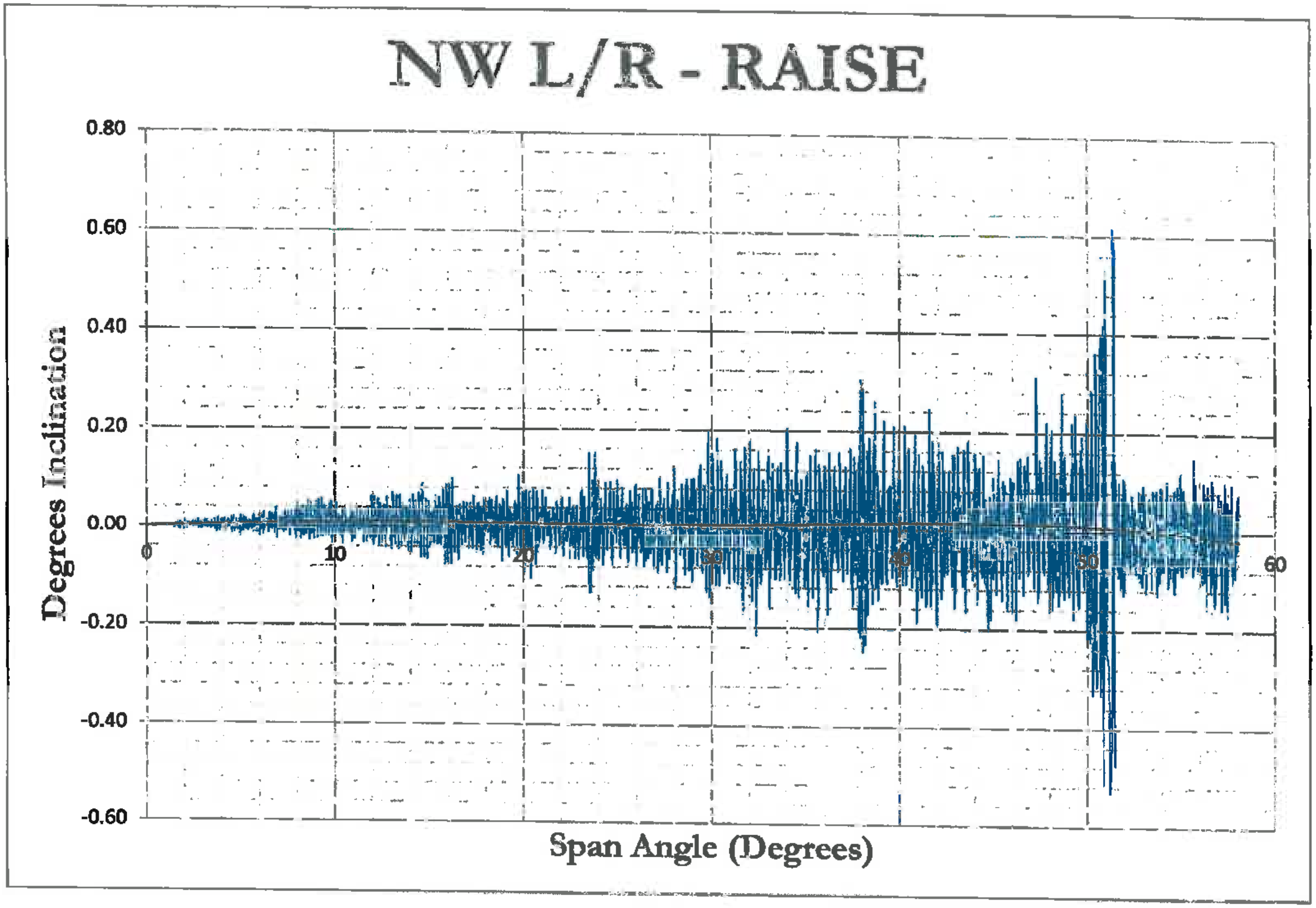
ANALOG DATA TRIAL #4



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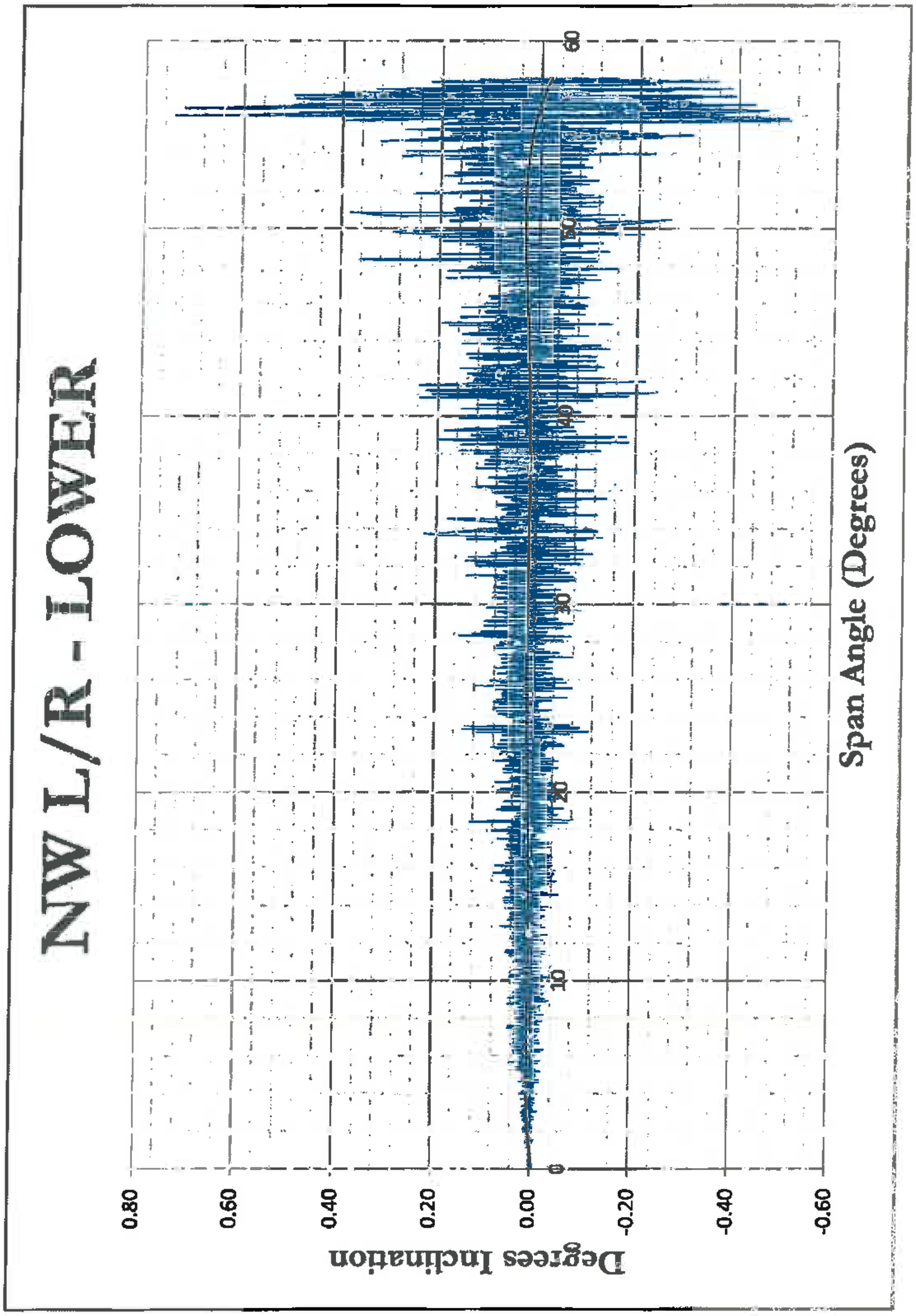

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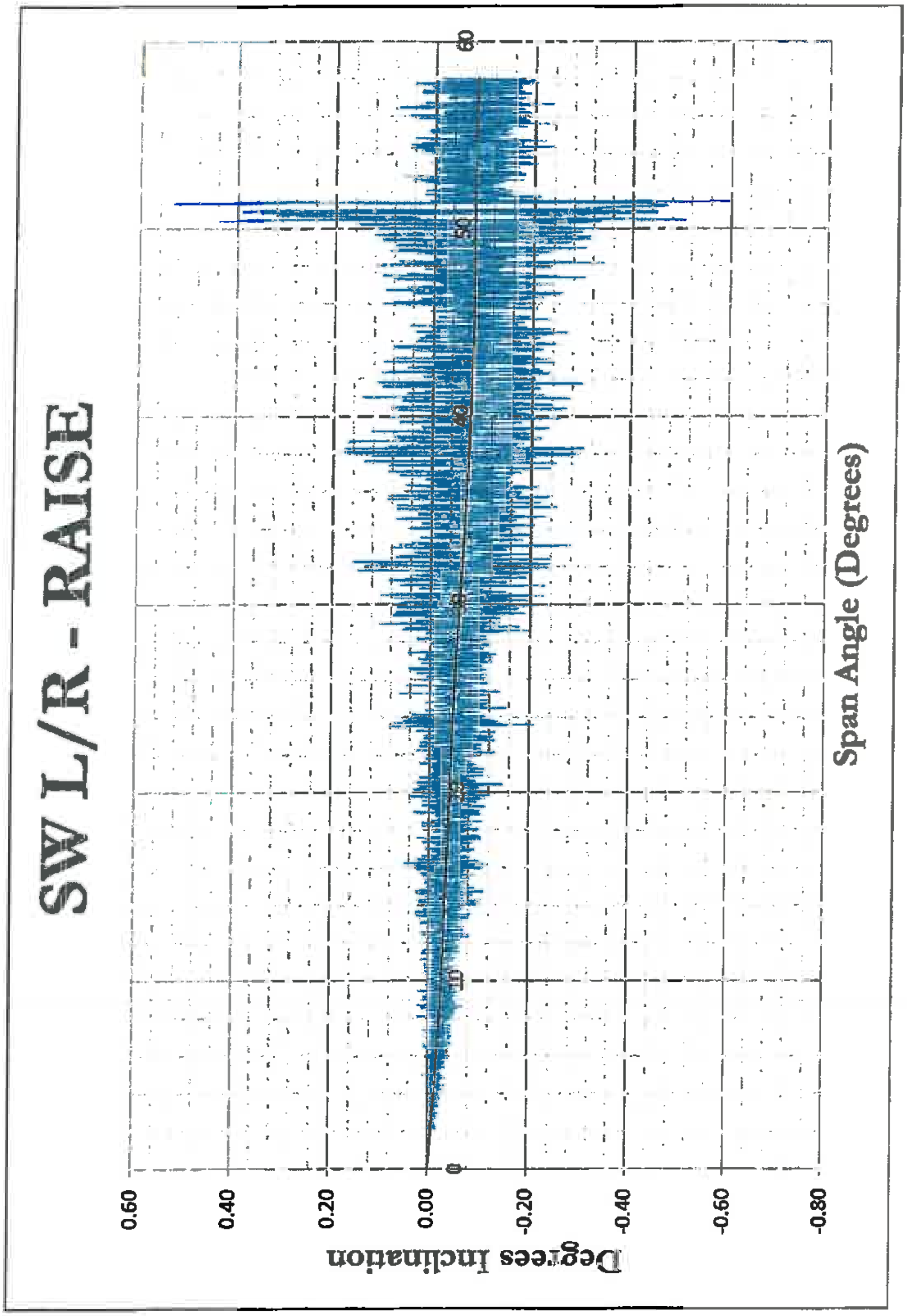
ANALOG DATA TRIAL #4



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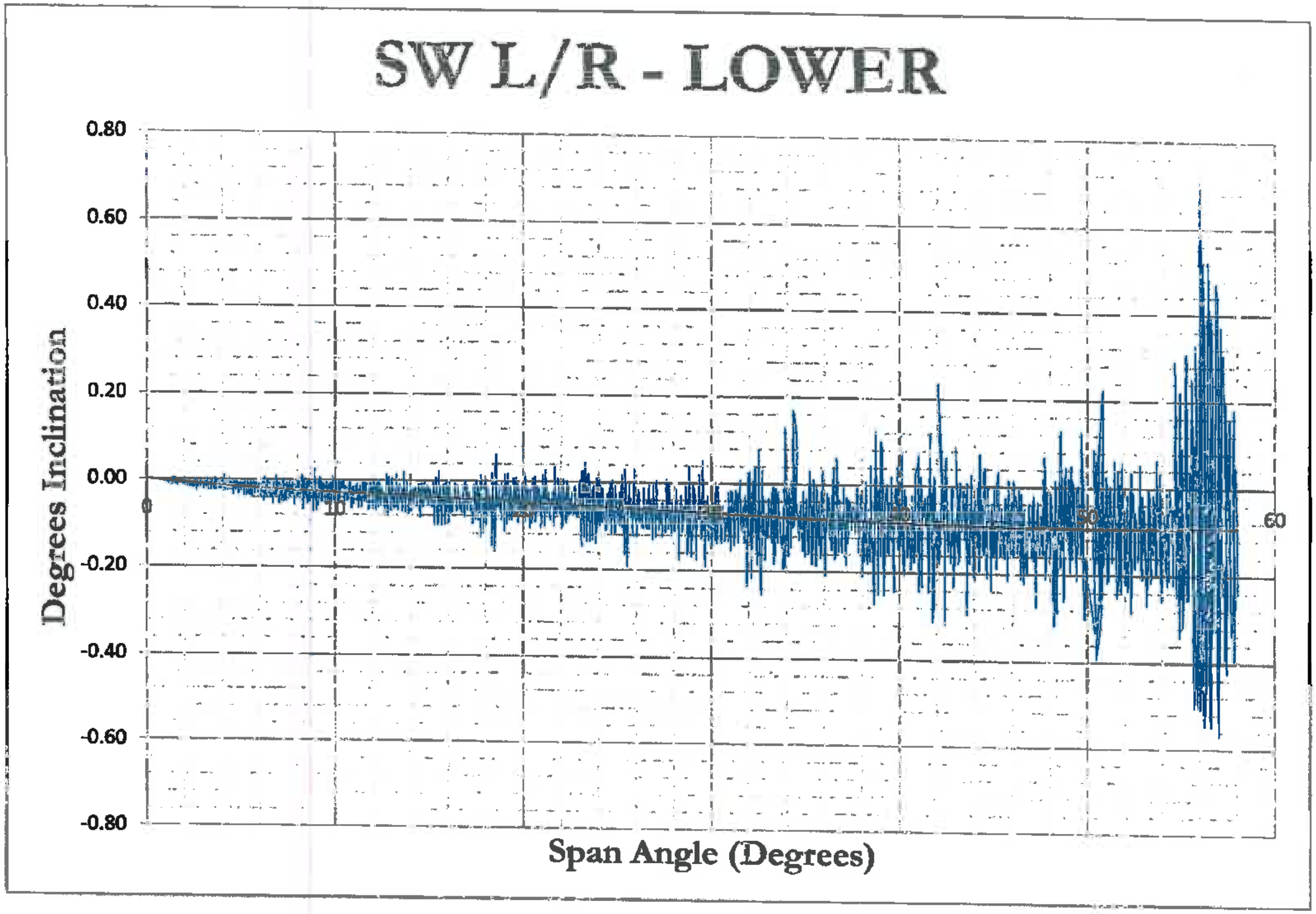
ANALOG DATA TRIAL #4



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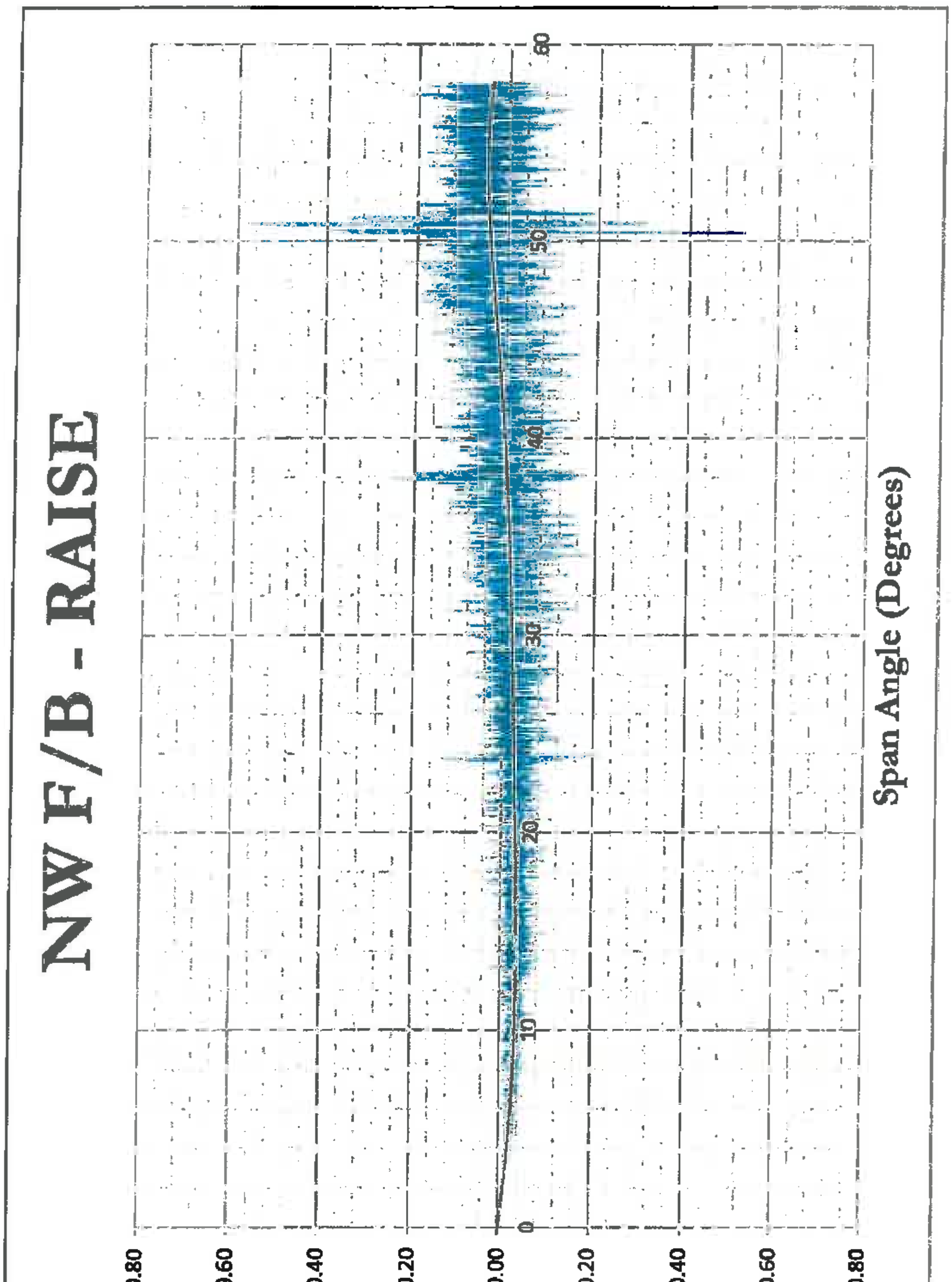

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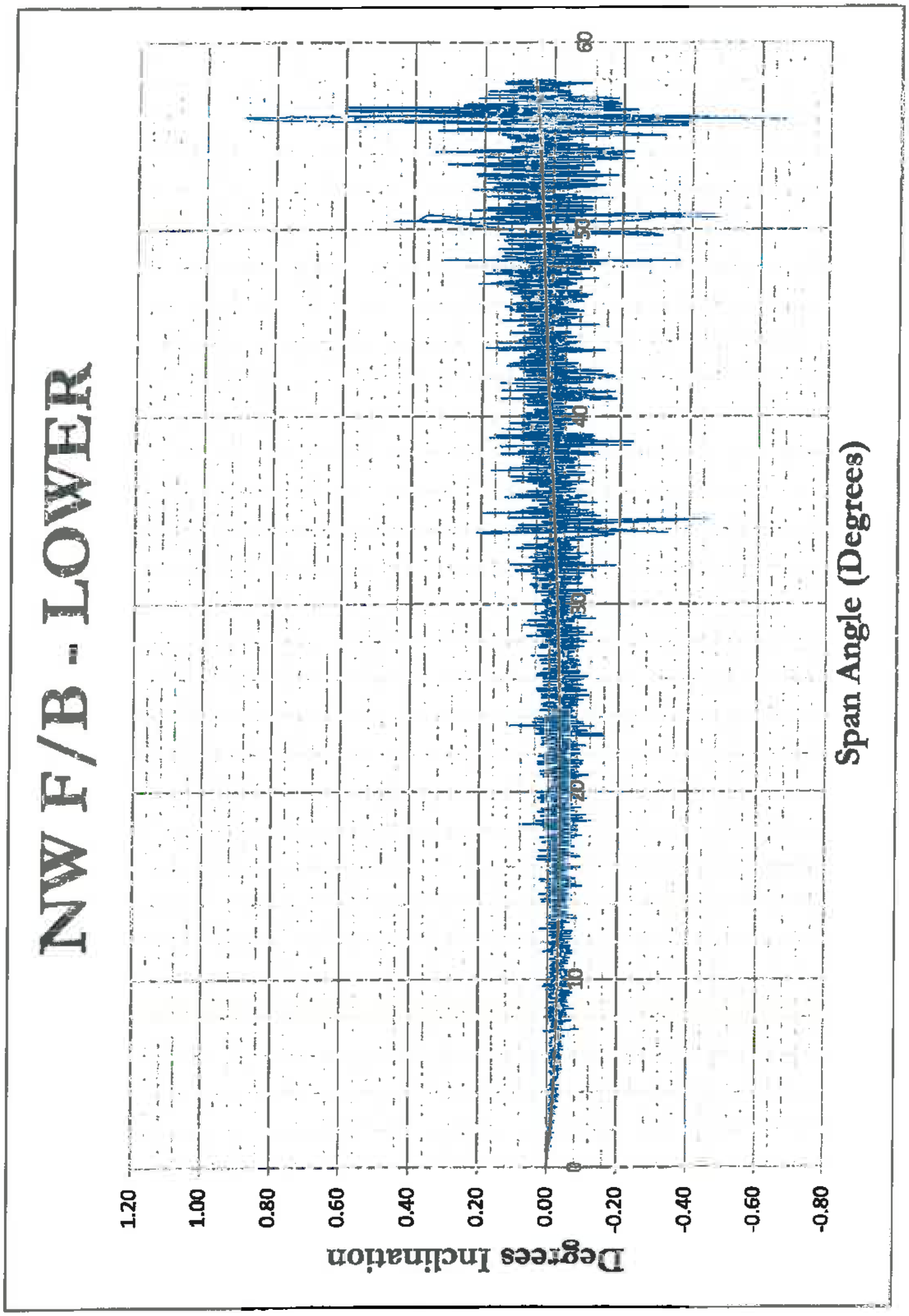
ANALOG DATA TRIAL #4



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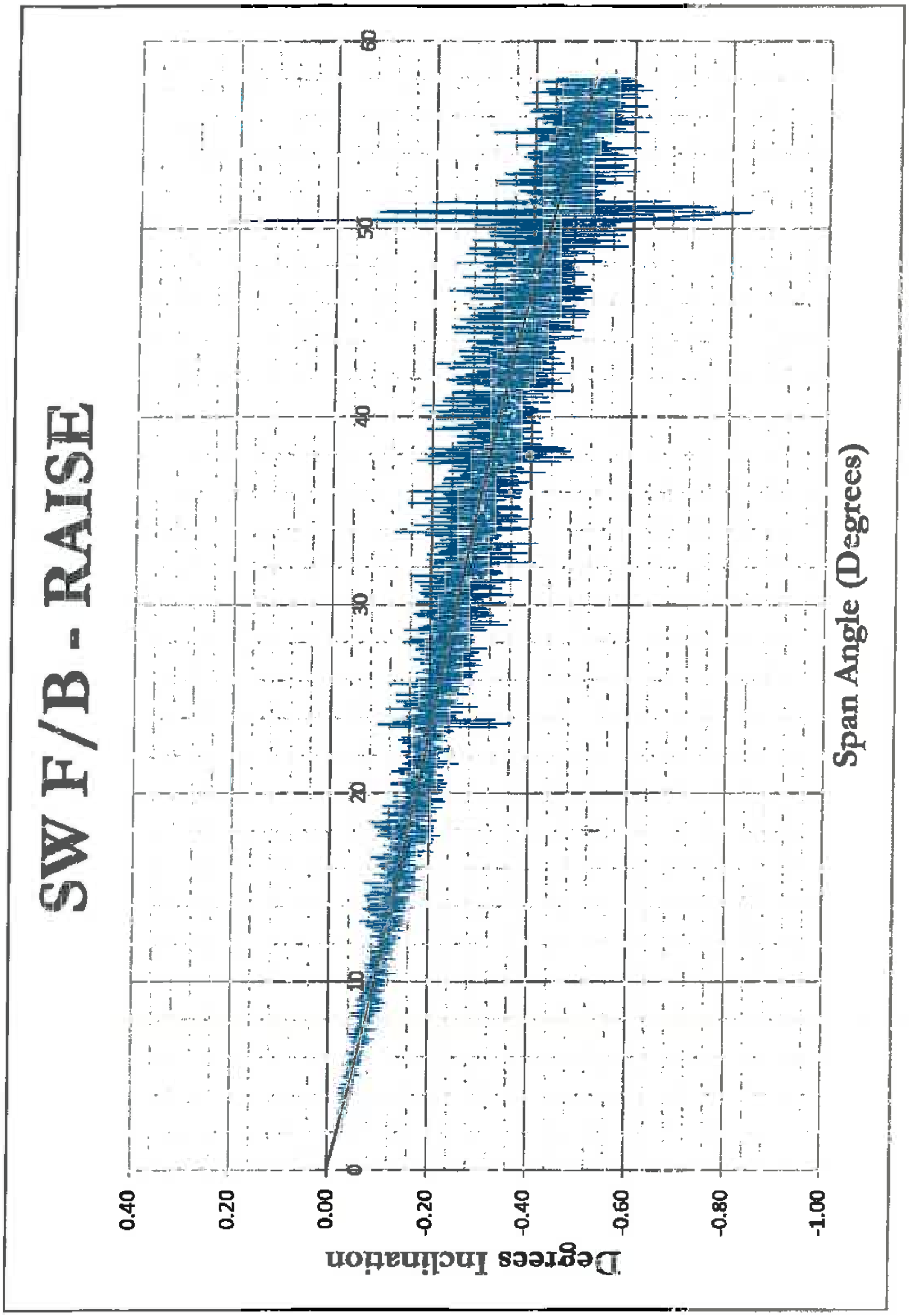
ANALOG DATA TRIAL #4



BROADWAY BRIDGE - 02720.00
WEST BRIDGE
ANALOG DATA TRIAL #4