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"The Effects of Balance, Friction and Control Sequencing on Span Skew and Seating During Lift Span Operation"

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THE EFFECTS OF BALANCE, FRICTION AND CONTROL SEQUENCING ON SPAN SKEW AND SEATING DURING LIFT SPAN OPERATION

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INTRODUCTION

Span skew and span seating problems are operational problems common to vertical lift bridges. However, the simple statement that a bridge has a skew problem, or a seating problem, does not address the cause of the problem, or what remedial action is required. This paper seeks to illustrate that skew and seating problems typically occur due to the confluence of several factors. In seeking to correct the span skew or seating problem, each contributing factor must be identified and evaluated on an individual basis.

Through inspections, operational testing and balance testing at multiple lift bridges, Stafford Bandlow Engineering, Inc. (SBE) has identified several factors as being key contributors to span skew and seating problems. These factors are system balance, system friction, system momentum, and electrical control and sequencing. This paper presents case histories at four vertical lift bridges and identifies the influence of the above factors in the behavior of these bridges.

CASE HISTORY COMPARISON				
	Marine Parkway Bridge	**CTDOT 02475**	**N.S. CD 182.30**	**Rt.1&9 over Passaic River**
Drive Type	Tower Drive	Tower Drive	Span Drive	Tower Drive
Span Length	540'	130'	265'	333'
Span Width	49.5'	60'	33'	72'
Rope Counter Balance	Auxiliary Counterweight	None	Auxiliary Counterweight	Balance Chains
Frequency of Operation	Low	Low	Extremely High	Minimal

CASE 1 - MARINE PARKWAY BRIDGE

The Marine Parkway Bridge is owned and operated by MTA Bridges and Tunnels. The bridge is a tower drive vertical lift span which carries Flatbush Avenue over Rockaway Inlet in Brooklyn, NY. The bridge is equipped with an auxiliary counterweight system to compensate for the weight transfer as the main counterweight ropes pass over the sheaves during operation.

SBE is currently performing strain gage balance testing at this bridge throughout an on-going rehabilitation project. SBE has performed five balance tests to date as part of this project. The focus of this case is on a seating problem which occurred during the fourth test performed on December 29, 1999.

During preparation for this test, SBE directed the operator to release the brakes so that a zero torque condition could be obtained in the machinery and the appropriate zero of the strain gage equipment could be obtained. This operation had been performed during all previous tests, and would be performed in all subsequent tests. However, the operator on the subject test was new.

When the brakes were released, the bride raised several inches. The operator attempted to drive the span locks following the zeroing operation to re-seat the span, however the locks would not drive. The operator's subsequent attempt to drive the span down in normal mode of operation was also unsuccessful in seating the span. The operator's perception of the cause for both of the failed attempts was that a severe counterweight heavy condition existed.

SBE had previously performed an in-depth inspection of this bridge in 1997 at which time this problem had been documented as follows. As the span was driven down during seating, the motors would de-energize and the span would rebound off the live load strike plates prior to coming to rest. More often than not, the span would have rebounded far enough that the span locks could not be driven. A limited investigation to determine the source of this problem with the machinery revealed that the span drive brakes did not set until after the motor had de-energized. This instant allowed for the span to drift, and the momentum of the span rebounding off the strike plates was sufficient to carry the span out of the operational range of the span locks. The temporary solution to this problem was that the operator would switch the drive to manual operation and re-seat the bridge, driving the span locks with the motor still energized.

This deficiency in the seating sequence had been reported but not corrected.

In the current case, SBE performed physical checks to ensure that span imbalance was not at fault. SBE released all brakes in the South Tower to observe the behavior of the span. If the span was sufficiently counterweight heavy, it would begin to rise on its own. No movement was observed. An attempt was made to manually rotate the motor shaft and open the bridge. The motor shaft could not be manually rotated in either direction. While this test did not indicate the magnitude or type of imbalance, it did indicate that imbalance was not sufficient to overcome friction; therefore the span could not open on its own when in the fully seated position. Therefore, the observed behavior of the span was attributed to the previously documented problem.

When the testing was eventually completed, the balance condition at the south end of the span, which exhibited the seating problem, was determined to be 7,700 pounds span heavy. This result emphasizes that span balance was not at fault for the seating problem.

CASE 2 – CTDOT BRIDGE NO. 02475

CTDOT Bridge No. 02475 is owned and operated by CTDOT. The bridge is a tower drive vertical lift span which carries Stratford Avenue over the Pequonnock River in Bridgeport, CT. The bridge is not equipped with compensating devices to account for the weight transfer as the main counterweight ropes pass over the sheaves during operation.

SBE performed a semi-in-depth mechanical inspection at this bridge in June 1998 as part of the State's biennial inspection program. At the time of the inspection the operator indicated that the bridge was experiencing skew problems. The span tended to skew at or near the extreme limits of travel after contacting the fully open or fully closed limit switch. Through the course of the inspection, SBE identified several likely sources for the skew. These sources include:

- A check of the rack and rack pinion gear tooth contact indicated that the span was counterweight heavy.

- The machinery brakes were providing inadequate torque. With the motor brakes hand released, the machinery rotated through the machinery brakes under the influence of system imbalance.

- The control sequencing provides for passive seating of the span. As in Case 1 above, a momentary float exists between the de-energizing of the motor and the setting of the brakes. This passive braking sequence allows factors such as balance, friction and external loads (wind, rain, snow, etc) to affect the behavior of the span. If friction exceeds imbalance, the span would move. Variations in loading end to end of the span caused by imbalance or friction would exacerbate a tendency to skew.

- The control sequencing provides for a passive initiation of the drive. The brakes release prior to the motor energizing. As a result a momentary float occurs allowing factors such as balance, friction and external loads (wind, rain , snow, etc) to affect the behavior of the span. If friction exceeds imbalance, the span would move. Variations in loading end to end of the span caused by imbalance or friction would exacerbate a tendency to skew.

The mechanical recommendations based on these findings were to verify the span balance, adjust the setting of the machinery brakes and adjust the sequencing of the brakes. Implementation of the three mechanical recommendations would mitigate the tendency of the span to skew.

CTDOT retained SBE to determine the balance condition of the lift span via the strain gage method, and to direct weight changes to improve the balance. A key consideration in determining the desired balance condition is that this bridge is not equipped with compensating devices to account for the shift in weight from the span to the counterweight as the main counterweight ropes transfer over the sheaves during span operation. Therefore, the balance change that is affected during span operation is solely a result of this weight transfer due to the main counterweight ropes. This balance change is a linear function based on the number of ropes and the unit weight of the rope. The governing factor in determining the optimum balance state is to minimize the work which the machinery must perform during operation. This is achieved by placing the balance point at the mid height; then the span is as span heavy when it is closed as it will be counterweight heavy when open. This equates to a span heavy condition of 3,279 pounds per corner in the fully seated position.

Over the course of several days in late August 1999, SBE performed the balance tests and directed weight changes to achieve the target balance state. Of particular interest are the peculiar and unpredicted behavior of the lift span under the weight changes and the crucial role of physical methods in achieving the final balance condition.

Results of the initial tests indicated that the bridge had a transverse imbalance problem. The South side of the bridge was reasonably well balanced, however, the North side of the bridge was considerably counterweight heavy. See Figure 1 at the end of this paper. The net effect of this balance condition was that the bridge was substantially counterweight heavy. An initial balance change was made in the counterweight pocket at the East end of the bridge. The subsequent test at that end of the bridge revealed that the weight shift did not achieve the desired result. Further weight changes were made followed by retesting. Once again, the physical changes did not produce the intended results. While each subsequent balance test indicated the total weight change that had been performed, the indicated changes did not occur at the expected corners. Likely sources for this phenomenon included a bottoming condition present at all rack and rack pinion locations that had an indeterminate effect on the loading in the transverse shafting, the severe transverse imbalance, and the location of the counterweight pocket at the center of the long narrow counterweight.

No action could be taken regarding the bottoming condition. However, the effects of the weight changes could be improved. Each counterweight was suspended by two groups of ropes, one at each corner. The addition or removal of weight at the center of the counterweight pocket produced an equal reaction in both groups of ropes. However, the severe transverse imbalance required that a substantial weight adjustment be performed at only one side of the counterweight. The centrally located pocket could not easily accommodate this need since any weight shift would produce a moment affecting both groups of ropes. The most effective means of changing the balance would be the placement of weight adjacent to the main counterweight rope terminations either at the counterweight or on the lift span to achieve a one to one relation. As the original design did not provide for weight adjustment at this location, a permanent means of securing the blocks would be required once the desired balance state was obtained.

While the strain gage testing provided quantitative results to direct the magnitude of the weight shift at the rope terminations, physical checks were essential in corroborating the strain data and verifying the acceptable behavior of the lift span in the final balance state. The physical checks were performed as follows. The lift span was stopped at various increments, the brakes were released, and the motor shaft was rotated by hand to check the resistance in each direction. Prior to the weight changes, the motor shaft freewheeled open with the span in the fully open position and could not be rotated closed with the span nearly seated. Following the final weight changes, the motor shaft could be rotated open in the fully open position and could be rotated closed with equal ease with the span nearly seated. Therefore the physical tests substantiated the acceptability of the strain gage test results.

Following the weight changes, the operator indicated that the behavior of the span was much improved. However, we are aware that the skew problem persists to this day. Correcting the imbalance problem alone was not sufficient to eliminate the skew problem. No action has been taken to date to change the sequencing of the brakes or adjust the setting of the machinery brakes.

CASE 3 – NORFOLK SOUTHERN BRIDGE CD182.30.

Bridge CD 182.30 is owned and operated by the Norfolk Southern Corporation. The bridge is a span drive vertical lift span which carries two tracks of rail over the Cuyahoga River in Cleveland, OH.. The bridge is equipped with an auxiliary counterweight system to compensate for the weight transfer as the main counterweight ropes pass over the sheaves during operation.

The Railroad was experiencing seating problems with the lift span that was attributed to a counterweight heavy condition. The Railroad retained SBE to determine the balance condition of the lift span via the strain gage method, and to direct weight changes to improve the balance. The desired balance condition indicated on the Original Contract Plans was a 3,000 pound per corner span heavy condition with the bridge in the fully seated position.

SBE was on site at the bridge in May 2000 to perform a limited in-depth inspection of the wire ropes and span support components, and to perform the balance tests. Two matters discovered during this field work are of particular interest. First, all sheave trunnions were heavily scored. The scoring of the trunnions at the operator's end of the span was roughly equivalent to a 500 microinch surface finish. The scoring opposite the operator's end of the bridge was much more severe, likely in excess of 2000 microinch finish with individual scores as deep as 1/32". This scoring was certain to result in increased friction which would be apparent in the strain data. Second, the operating ropes at one corner of the span were slack and had to be adjusted in order to obtain a zero torque condition in the instrumented shafts for the balance tests. NS personnel indicated that variations in the operating rope tensions were common, and frequent adjustments were required to keep the ropes taut.

The following table presents the results of the analysis of the strain data with the span in the fully seated position.

TEST RESULTS, RUN 2 May 11, 2000			
	NE Corner	**SE Corner**	**East End**
Initial Imbalance lb.	-6,901	-2,069	-8,986
Average Friction lb.	12,263	8,450	20,729
	NW Corner	**SW Corner**	**West End**
Initial Imbalance lb.	373	-1,203	-829
Average Friction lb.	2,450	4,545	6,994

None of the corners meet the 3,000 pound span heavy condition specified on the Original Contract Plans. In fact, three of the four corners are counterweight heavy and a substantial discrepancy exists in the balance end to end of the span. A substantial difference also exists in the friction from end to end of the span. This difference is corroborated by the noted variations in the extent of the wear at the various trunnions, with the trunnions exhibiting the worst wear having the highest friction. The greatest friction, which is present at the NE corner, is over 5 times greater than the least friction, which is present at the NW corner.

A characteristic of span drive lift bridges is that both ends of the bridge are driven off common machinery. Therefore, skew due to transverse and longitudinal variations in imbalance and friction should not be a consideration. However, when the operating ropes for a given corner of the span are slack, that corner is not actively driven but rather is carried along through the rigidity of the structure. This could result in a corner of the span not being driven down during seating. The span seating problem is therefore attributed to the slack operating ropes exacerbated by the counterweight heavy balance condition.

The following actions will be taken to address the seating problem. NS personnel are aware of the tension variations in the operating ropes and will monitor these ropes to ensure that they remain sufficiently taut. Weight changes will be performed to bring all corners into balance per the Original Contract Plans. The resultant span heavy condition will have a tendency to seat the span.

In closing, Norfolk Southern intends to rehabilitate the trunnion journals to eliminate the scoring that was discovered as part of this work.

CASE 4 – U.S. ROUTE 1 TRUCK OVER THE PASSAIC RIVER

U.S. Route 1 &9 Truck Bridge over the Passaic River is owned and operated by the NJDOT. The bridge is a tower drive vertical lift span which carries the aforementioned road over the Passaic River in Jersey City, NJ. The bridge is equipped with balance chains to compensate for the weight transfer as the main counterweight ropes pass over the sheaves during operation.

SBE is providing strain gage balance testing services to monitor the balance condition of this lift span over the course of an on-going deck replacement project. The initial balance tests were conducted on May 21, 2000. Tests had been attempted two times previously but had been halted on both occasions due to operational problems with the lift span. Due to the high traffic volume carried by this bridge, delays to traffic are undesirable. Therefore, the tests were conducted over the weekend during an early morning closure to minimize the impact on the traveling public.

Known operational problems with the lift span include a tendency to skew when approaching the fully closed position and seating problems. NJDOT have attempted to rectify the seating problem by adding balance blocks to the problematic corner of the span. Known physical conditions include a friction problem at one of the trunnion bearings and a deteriorated submarine cable.

One of the key assumptions of the dynamic bridge balance method is that friction is constant throughout lift span operation. If friction is not constant, or if friction varies considerably from raising to lowering of the span, the analysis may produce erroneous results. This case is of interest due to the presence of substantial friction in the system. The following is a discussion of those steps taken to identify the friction and those steps taken to analyze the data despite this significant hindrance.

The excessive system friction was revealed through the recorded data in four ways.
1. Non repeatability of the magnitude of the torque signature.
2. Non repeatability of the general characteristic of the torque signature.
3. Amplitude of the torque signature.
4. Fluctuations in the signal.

The first two items were revealed through comparison of traces from subsequent runs. As there is no way to directly measure friction, a reasonable check is to demonstrate repeatability of the torque signatures from the drive. Typically three openings are conducted for a balance test to demonstrate repeatable behavior. Typically the tracings from these three openings are near identical. The traces for the subject bridge varied in magnitude from run to run, and also exhibited variations in general appearance.

The third and fourth items are apparent through comparison of the torque signature from the subject drive against a signature from a similar bridge. Figure 2 is the torque signature for NS Bridge CD182.30 discussed in Case 3. Figure 3 is the torque signature for the subject bridge. Figures 2 and 3 are located at the end of this paper. The actual balance curves are innately different for these bridges, as the curve for Figure 2 is a sinusoid and the curve for Figure 3 is linear. However, the startling difference in the amplitudes of the signatures is immediately apparent. The nominal amplitude of the signature in Figure 2 is roughly 5 microstrain. The nominal amplitude of the signature in Figure 3 varies from 5 to 80 microstrain. Discounting the effects of acceleration and deceleration, it is typical to have fluctuations in the signal due to periodic drive system events such as the meshing of gear teeth, however the nominal amplitude of the signature should be constant as seen in Figure 2. The random fluctuations in the signal apparent in Figure 3 that result in the non constant amplitude of the torque signature can only be attributed to friction.

Given the above problems, it is valid to question the reliability of the results obtained through this data. However, consideration must be given to the fact that in field work we are confronted with circumstances that are not ideal. The data obtained through this testing, through problematic, is the actual torque signature for this bridge. Therefore, multiple analyses were performed on the data to obtain the best possible results within the existing constraints.

Analyses were performed on the data from all runs conducted as part of this testing. Results for a given run were compared through iterative sample rates, and results from subsequent runs were compared against each other. The results of the analysis for each corner, while not approaching the repeatability expected through previous tests, did exhibit relative consistency and indicated a wide spread in friction and imbalance end to end and corner to corner of the lift span. The combination of these factors indicates some reliability of the results. Given the constraints of the current case, the only method of increasing the reliability of the test results would have been to retest following a known weight change. This known weight could then be used to check or calibrate the test data. Due to the limited closure period under which the current test was conducted, this option could not be pursued.

The results of the analysis indicated that all corners of the span were span heavy with the imbalance at one corner approximately 3 times greater than at the remaining corners; this corner corresponded to the corner that NJDOT personnel had added balance blocks in an unsuccessful attempt to alleviate the seating problem. Calculated friction varied as much as 5 times end to end and as much as 10 times corner to corner of the lift span. Although no attempt was made to identify the source of friction in the subject case, we have seen that in Case 2 a variation in friction of 5 times corresponded to significant damage of machinery components.

While these test results have not established the source of the skew or seating problem, they do provide some basis to investigate or troubleshoot the problematic conditions. Though all corners of the span are span heavy by varying amounts, the friction is well in excess of the imbalance at one end of the span and is a likely contributor to the seating problems. To correct the skew and seating problem, it may be necessary to correct or mitigate the friction problem. External factors that could contribute to system friction include, but are not limited to, the trunnion bearings, with a problem already diagnosed at one bearing, as well as the span guide system and the counterweight guide system.

CONCLUSIONS

Span skew and seating problems though common to all vertical lift bridges differ in occurrence. Each problem must be evaluated individually, and the root cause determined. The above cases illustrate the following points:

1. Where imbalance exceeds friction, the span can and will move if not stayed. Therefore, active braking sequence are preferred to prevent skew. Typical incidents of skew occurring at or near the fully open and fully closed limit switches are due to the confluence of the maximum points of imbalance with momentary float in the drive system allowed by the braking sequence.

2. An active seating sequence will eliminate span seating problems. Live load shoes should be driven into the fixed strike plates and the brakes applied prior to the de-energizing of the motor. This will prevent rebound and ensure that the bridge is firmly seated.

3. Lift spans should be span heavy in the fully closed position to prevent any tendency to raise during seating.

4. Strain gage testing is an effective means of quantitatively determining system balance, however it must be performed with proper physical checks to ensure the best results. These checks include physical verification of a zero torque condition in the instrumented shafts to establish a baseline for the test, physical check at various points throughout test to ensure that physical system corroborates data provided by gages, and, where possible, direct calibration of system through weight changes. The number and type of checks is dependent upon the existing system, however the more steps that can be taken to corroborate the test data, the more reliable the results.

5. Strain gage testing may be used to chart drive train performance. In particular, system friction may be monitored. As substantial increases or discrepancies in system friction have been proven to be indicative of extensive machinery damage, baseline readings early in the life of the bridge can be used to identify and isolate deteriorating components in the future. This could provide the early warning necessary to avoid a costly rehabilitation.

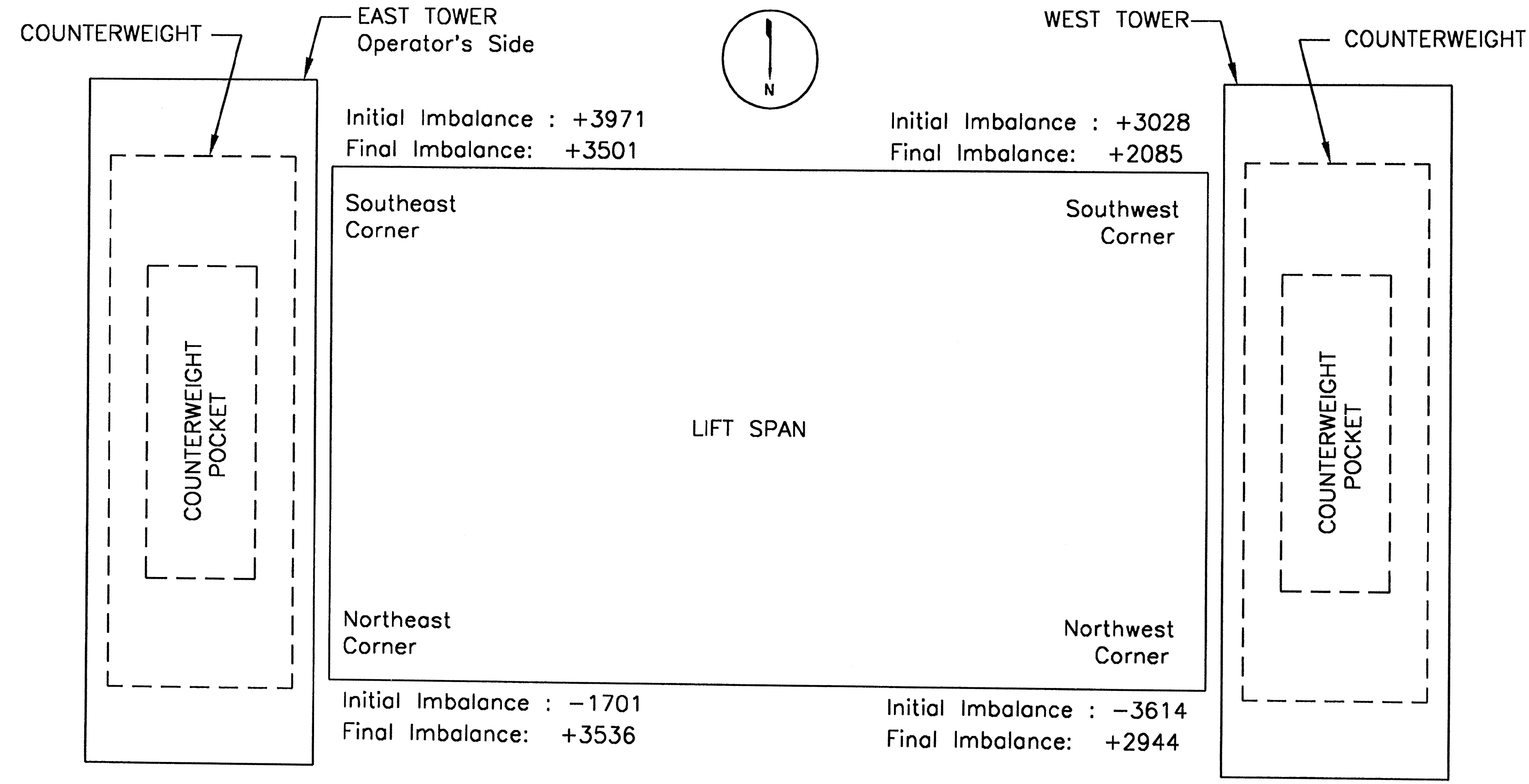

Figure 1. Plan View of Movable Span and Documentation of Balance Test Results

	Project: CTDOT Bridge 02475 Bridgeport, Connecticut Balance Tests August 1999	Prepared for: Heavy Movable Structures 8th Biennial Symposium Lake Buena Vista, Florida Prepared by:

FIGURE 2
NS Bridge CD 182.30 over the Cuyahoga River
Strip Chart Data - SW Corner, Run 2

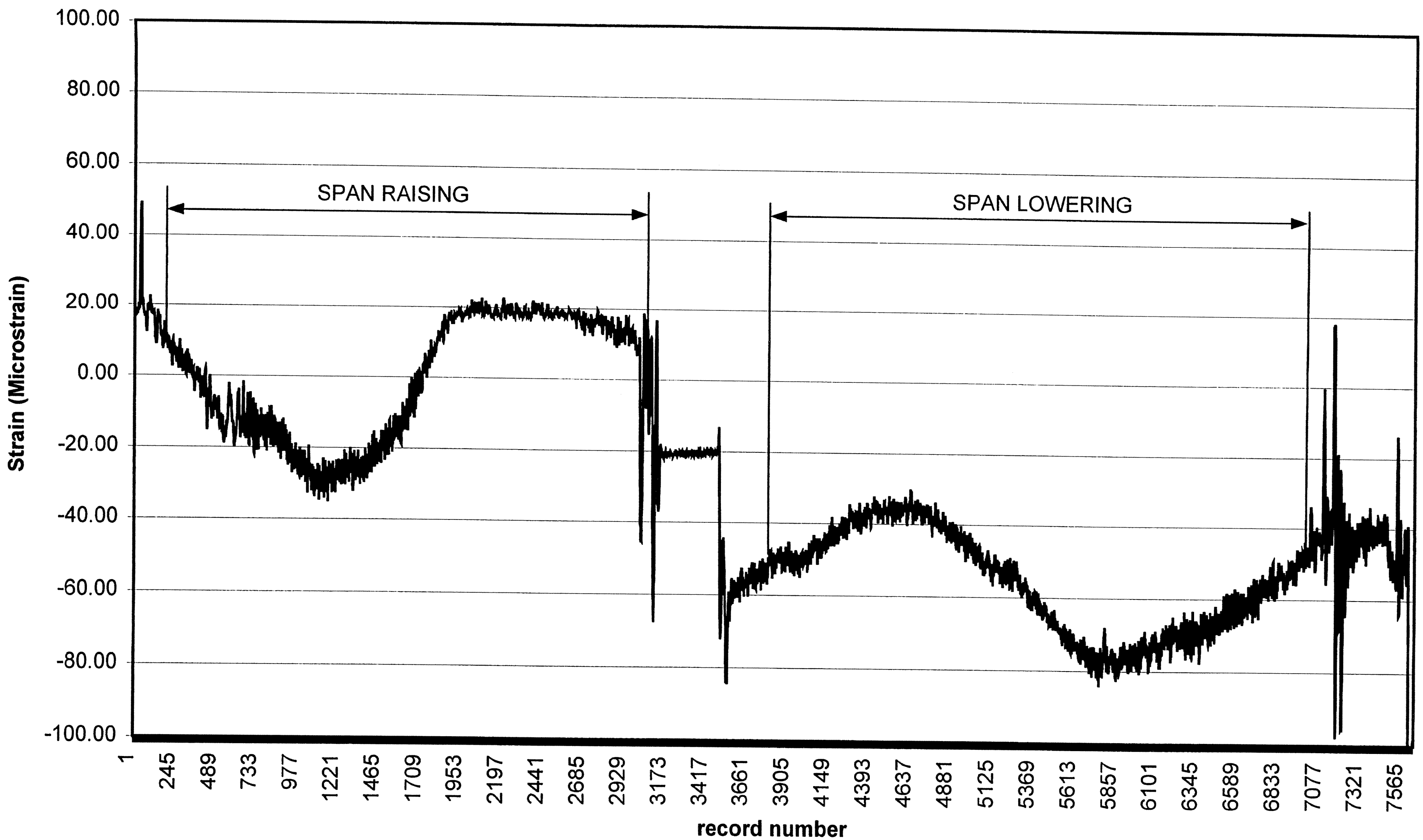

FIGURE 3
U.S. Route 1&9 Truck Bridge over the Passaic River
Strip Chart Data - West Tower, North Corner