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Madison Avenue Swing Bridge Mechanical and Electrical Rehabilitation

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The Madison Avenue Bridge crosses the Harlem River in New York City, NY making it a vital artery between the boroughs of Manhattan and the Bronx. Opened to traffic in 1910, it replaced a smaller swing bridge that was completed in 1885. The original 1910 Madison Avenue Swing Bridge's mechanical drive system was designed around electric motors that drove the open gears to power a rack and pinion system that set the bridge into motion. The system was considered leading technology at the time.

The Madison Avenue Bridge in total is nearly a mile long, with the 304'-7" steel cantilevered truss swing bridge being the dominating feature of the piece of infrastructure. Over the bridge's 114 years of service, much of the approach structures have been replaced or significantly rehabilitated to accommodate the changing landscapes of the area (such as the west side accommodating the Harlem River Drive). The truss and drum girder systems were essentially original with the cantilevered swing span is made up of historic riveted-steel decorative trusses which sit atop a 6 ft tall by 49'-8" diameter drum girder. The bridge is driven through a pair of electric motors that turn the span drive, which are comprised of a set of reducers.

The scope of the current contract was based around the complete replacement of the mechanical and electrical drive systems with a modern system intended to extend the bridge's life for decades more to come while improving the access and safety needs of the public and those responsible to operate and maintain the vital asset. The new improved systems have been customized to fit within the constraints of a structure designed for the access and safety expectations from over 100 years ago. Further, the design had to consider the constructability and permitting requirements that required only off-peak lane closures and a single 3-month navigation channel closure.

Many of the features are intended to minimize maintenance and improve reliability moving forward. Examples includes having a backup diesel hydraulic power unit, electrical power feeds from both the Manhattan and Bronx shorelines and rack and pinion maintenance platforms. This included a full replacement of the 54-foot diameter rack that employed a laser tracking process to ensure the new rack would fit correctly to the existing center pier. The new 56-foot rack was accompanied by new pinions that were detailed with crowning of pinion teeth to accommodate misalignment and retrofitted with a center post bushing to control movements. In addition to the mechanical enhancements, the electrical systems have been have brought into the 21st century including redundant controls and paths for power. The design of the bridge's new electrical system allows safe control of the bridge remotely from both gate houses as well as the operator's house above the center pier. These features are just a few resiliency enhancements to the bridge to ensure moving forward the bridge remains functional for whatever it may be exposed to; including future Superstorm Sandy-level catastrophic events.

NYCDOT Infrastructure Asset Benefits from Saving this Bridge.

The Madison Avenue Bridge remains one of the key connections between Upper Manhattan and the Bronx. It carries nearly 50,000 vehicles per day along with two full-size pedestrian sidewalks. During the preliminary design phase of the current rehabilitation project of the Madison Avenue Bridge, NYCDOT, supported by Parsons, confirmed that the existing bridge was in a good state of repair, but the mechanical and electrical systems were outdated and quickly becoming a constant maintenance issue for NYCDOT. NYCDOT saw the opportunity to save the Madison Avenue Bridge while modernizing its functionality and reducing future maintenance needs. From an asset planning perspective, this provides both near-term and long-term value to NYCDOT and the community the infrastructure supports.

From a near-term value perspective, saving the bridge meant minimal disruption to the community, as the bridge and the route remained open throughout the project. Replacing the bridge, given its level of local connectivity, would have been disruptive to the community at large, much as was seen in the replacement of both the Third Avenue and Willis Avenue projects. From a financial perspective, replacing the Madison Avenue Bridge would have cost multiple hundreds of millions of dollars. Over the last 15 years, NYCDOT has replaced two adjacent crossings, the Third Avenue Bridge and the Willis Avenue Bridge, at a combined cost of nearly $900 million. However, the cost of the mechanical and electrical rehabilitation was approximately $50 million. By saving this structure, significant financial resources can now be allocated to many other NYCDOT assets that are in need of attention.

From a long-term perspective, the bridge is vastly more resilient than it previously was. We learned after Super Storm Sandy that environmental events can cause significant disruption to infrastructure that was never envisioned when it was built over a century ago. Madison Avenue Bridge can now be operated not only from the operator’s house but also from both the Manhattan and Bronx sides. The bridge is now equipped with backup power supplied by an onsite diesel generator, meaning if power is lost from the shore the moveable bridge can still be operated if needs from the waterway are identified. From a maintenance perspective, multiple improvements have been included. Examples include:

- The replacement of the original open gearing used to drive the pinions with enclosed mechanical equipment.
- The end lift equipment is no longer suspended off the truss but is relocated to the rest piers, which improves access for maintenance.
- Access enhancements have increased worker safety. This includes platforms around the rack, modern hatch doors, and ladders down to the rest piers as well as within the machinery room.
- The replacement of the existing equipment increased the usable space within the machinery room.
- An upgraded CCTV system providing nearly 360-degree views above and below the bridge, ensuring improved safety during bridge operation for the community as well as the maintenance forces that will operate and maintain the bridge.

Rehabilitation of structures as old as the Madison Avenue Bridge is often difficult. This structure was designed for a community and needs never envisioned in the 21st century. It has been modified multiple times to remain functional, meaning that fit-up and adapting to field conditions are imperative to successfully saving the structure. By saving the Madison Avenue Bridge, NYCDOT has made a significant investment in their overall infrastructure inventory, reduced their maintenance overhead for years to come, and significantly minimized the impacts on the community.

Machinery

During the past 100 years and over 50,000 openings since the original construction, the machinery systems have been rehabilitated more than once. However, the center post, rack, tracks, span support rollers remained original. The span drive machinery had been rehabilitated by replacing various components but maintaining the same configuration. This rehabilitation replaces the rack and creates a machined journal on the center post. The span drive machinery with open gears has been replaced with a new machinery system using enclosed reducers and roller bearings. The individual span mounted end lifts are replaced with a pier mounted three end lift system. The existing centering locks on either end of the bridge are replaced with new assemblies that are similar to the existing. The bridge originally had a vertically moving latch bar with a counterweight and spring-loaded receiving socket.

The Madison Avenue swing span is an early example of the transition from combined rim and center bearing to the rim bearing swing bridge. The early combined rim and center bearing typically had a center bearing that was a semi-sphere and a portion of the dead and live loads were carried by the center bearing. A rim bearing swing bridge carries no vertical loads at the center post. The live ring and the swing span are typically restrained radially at the center post. At the Madison Avenue Bridge, the drum girder and the live ring have radial struts that are connected at the center with gusset plates at the top and bottom of each set of 12 struts. The original plans showed 1” thick gusset plates had a bore with 1/32” clearance around the center post. During an inspection prior to developing the rehabilitation plans, the clearance between the gusset plates and the center post was found to be larger and combined with anticipated further wear may have allowed undesirable radial deviation causing varying center distance between the pinions and the rack. To prevent this relative movement between the rack and pinion the journal of the center post was machined in situ and a bronze bushing was installed in the upper gusset plate of the drum girder.

Span Drive Machinery

The span drive machinery converts the torque and speed of two alternately energized foot mounted horizontal shaft motors to the low speed and high torque required at the vertical pinion shafts. Both span drive motors are connected to opposite ends of the input shaft of a double reduction parallel shaft differential reducer. Each output shaft is connected to the secondary reducers using a supported shaft and floating shafts. The differential on the output shaft equalizes the torque between the output shafts and therefore to the secondary reducers and the pinions. An auxiliary input shaft is located at the high-speed end of the reducer at a right angle to the other shafts. A bevel gearset connects this shaft to the input shaft with a ratio of 1.5:1. This input shaft rotates whenever a motor is energized. A cut-out coupling allows connectivity with the backup hydraulic motor.

The secondary reducers are double reduction spiral bevel right angle reducers with one parallel shaft vertical gearset as well. The input shafts are horizontal, and the output shafts are vertical. The north and south secondary reducers are identical to each other externally but internally the bevel gear is positioned either above or below the bevel pinion to cause the output shafts to rotate in the same direction as each other. Additionally, the low-speed output shafts have a dry well to prevent oil pressure on the output shaft seal from causing a leak.

Motor brakes are provided on the input shaft of the primary reducers and machinery brakes are provided on the input shafts on the secondary reducers. All brakes are thruster type, spring set electrically released.

Rack and Pinion

The existing rack was a full circle around the pier and the span was capable of opening 90 degrees in either direction. It had worn locations at the fully closed and open positions where the tooth loads were greatest due to overcoming the starting friction and inertia. There were 32 segments with a total of 64 connections between the existing rack and the track chair. Each segment had two bolt connections at each end and a four-bolt connection at the center.

A new rack was designed to be integrated into to the existing track chair at the same locations as the existing rack but with an intermediate support at each connection. The new rack has a diameter greater than the existing. The new rack consists of 16 segments and each segment is connected to a support at each end using two turned bolts and to three intermediate supports with four bolts. The supports are connected to the track chair at the same 64 locations as the existing rack, providing improvements to constructability and ensuring tighter fit up tolerance by reducing the installation count from 32 segments to 16 segments. Four turned bolts and shims are used at each location to provide opportunities to adjust the alignment between the pinion and rack teeth. The existing bolt holes in the track chair were enlarged and the new holes in the rack support were undersized until final fit-up and adjustment. Prior to field installation, the entire rack was assembled together with the supports and mounted on a vertical boring mill at G&G's Warrior River, AL facility. The facility set up the supports and layout based on the field laser tracker information, allowing verification of the new rack prior to field installation. Verification of fit-up of the new rack assembly was validated through confirming the radius, concentricity, circularity radial and tangential tilt. The validation utilized with a laser tracker system and correlated to the located center of bridge. A target was located on a pitch pin and sequentially moved to different locations. The installation of the rack on the track chair was verified using a laser tracker. The shim thicknesses between the new rack supports and the existing track chair were adjusted to reduce the extremes of backlash as well as tilt the rack radially to improve the local contact between the gear tooth flanks.

The existing 14 tooth pinions had been replaced two times in the past due to wear and usage and were now being replaced with 18 tooth pinions and therefore have a larger diameter with a similar pitch. The new pinion teeth had tip and root relief to prevent interference as well as end relief (crowning) to minimize end loading.

The existing center/pivot pier had no access platforms or any safety railing around its perimeter or attached to the drum girder making access and maintenance of the rack and pinion assemblies challenging. The larger diameters of the new rack and pinions necessitated a platform which was enhanced with a modern safety railing system around the pier to provide safe access for inspection, lubrication and other maintenance. The new platform includes a grid floor, and railing with a kick plate. The layout was sized to ensure there is sufficient room for the pinion to pass by a stationary worker as the span rotates. The elevation of the platform floor is approximately the same as the elevation of the pier top stone.

Hydraulic Auxiliary Span Drive

The swing span has an auxiliary diesel-hydraulic drive that will function in the event of a complete electrical failure from all sources. The diesel engine has an alternator, battery and starter and can be started in the absence of utility power. The pump is connected to a control valve which is connected to a hydraulic motor. The motor is disconnected from the primary reducer using a cut-out coupling when the swing span is to be rotated by an electric motor. The cut-out coupling of the hydraulic motor is engaged with the primary reducer when the swing span is to be rotated with the hydraulic motor.

End Lift System

There are three end lifts per rest pier aligned with the three trusses of the swing span. The existing design had individual end lifts, each with its own motor at each end of each truss. The six individual end lifts were span mounted eccentric roller end lifts driven using a helical/worm reducer and chains which were installed in the 1990s. These replaced the original end lift system which was span mounted scissor style lifts with all the three at each end of the span mechanically synchronized with transverse shafting and driven with one motor.

One of the goals of this rehabilitation was to locate the end lift machinery on the rest piers and using one motor per rest pier to drive the end lifts, significantly reducing the maintenance needs for NYCDOT. Eccentric rollers consisting of a steel roller with two internal solid flanged bushings and an eccentric shaft inside were located under the ends of each truss. The three end lift eccentric rollers on each rest pier interconnected with floating shafts and couplings. This was similar to many of the new Harlem River swing bridges. A two-inch eccentricity was selected to provide four inches of vertical displacement of the roller. The four inches of displacement provides at least 2 ½ inches of clearance between the tops of the rollers and the load plates on the swing span. To maximize the vertical space available for machinery a 34” roller diameter was selected. The reducer height was constrained by the height of the roller in the lowered position, about 15 inches above the shaft centerline. To optimize the limited space on the rest pier, three reducers (one primary and two secondary) are used. The two secondary reducers share the torque in smaller housings rather than one larger secondary and are located in between each of the three end lifts. The two ends of each secondary reducer output shafts are connected to the three end lifts using floating shafts and single engagement gear couplings. The center end lift is driven from each secondary reducer. The north and south end lifts are driven by the secondary reducer output shafts opposite the shafts connected to the center end lifts. There are no differentials in the secondary reducers and the output shafts, floating shafts and eccentric shafts are all synchronized with each other. The configuration of the long series of shafts interconnecting the three end lifts to the two secondary reducers are laid out to accommodate any imbalance between the torque demand of the end lifts. The torque into and out of the secondary reducers is always equalized by the differential on the output shaft of the primary reducer. The differential also allows for the total backlash (with a tolerance in each gearset) in each reducer to be on the non-driving side in both directions.

Additional to the vertical space constraint, there is also a horizontal space constraint for the end lift machinery in the bridge longitudinal direction. The primary reducer input shaft which is also the motor shaft is closer to the end lift roller shaft than the primary output. This allows placement of the motors between the end lift floating shafts and the floating shaft connecting the primary reducer output shaft and the secondary reducer input. The motor splice enclosures are located on top of the motors due to insufficient space on the sides. Two alternately energized motors are connected to the primary reducer input shafts.

The end lift auxiliary drive is designed to use either a hand crank or drill motor connected to a worm drive reducer to move the end lifts at a much slower speed in the event of a power or control failure. The 40:1 ratio worm reducer has a hollow output shaft that with a sliding shaft is able to connect to the end lift motor if there is power or control failure. When auxiliary drive operation is necessary the cover on the opposite drive end of the motor is removed exposing a round shaft end with a keyway. The sliding shaft within the hollow shaft is slid into engagement with the motor shaft to enable manual drive for the end lift. During testing there was no tendency for the end lift to back drive.

A rotary cam limit switch and a U-5 railroad style limit switch are connected to the outboard ends of the north and south eccentric shafts. The direct drive rotary cam limit switch remains synchronized if the eccentric shafts rotate more than 360 degrees.

Centering Lock

There are two centering locks with vertically moving lock bars mounted to the end floor beams at each end of the swing span that engage receiving sockets at each rest pier. The receiving socket has three main pieces to provide adjustment for field alignment of the swing span closed position. Existing stainless steel anchor bolts were reused to avoid drilling additional holes in the granite blocks in close proximity to the existing bolts.

A helical/worm gear reducer is used to reduce the motor speed. The reducer output is a hollow shaft with two piece forged steel crankshaft inserted into the bore. The crank arm length is 9 inches and 180 degrees of rotation causes the bar to lift and lower 18 inches. A connecting rod converts the rotary motion of the crankshaft to the linear vertical motion of the lock bar. The connecting rod uses a universal joint at the bottom end to restrain the rod against axial rotation. The top end uses a spherical roller bearing which does not restrain the connecting rod against rotation about the rod axis. These joints and bearings prevent forces due to misalignment from developing and binding throughout the range of motion.

One of the benefits of using a crankshaft is the ability for the machine to rotate 360 degrees and continuously rotate if the limit switch controlling the motor fails. The rotary cam limit switch is connected to the worm shaft (the intermediate shaft of the reducer) with a small worm gear reducer with the same ratio as the worm in the main reducer. This keeps the limit switch synchronized if the machine is rotated 360 degrees or more.

Span Position Sensing System

The span position sensing system measures the relative rotation of the swing span to the rest pier using a shaft directly connecting the instrument drive gearbox to the center post.

The rotary cam limit switch, resolver and selsyn transmitter are mounted to the swing span in the machinery room. A position indicator used by the operator when the span is swung using the hydraulic motor is located in the machinery room and connected to this instrument drive system. The indicator has a fixed pointer shaped like the swing span and graduated disc with bronze plates representing the fender system and Bronx rest pier that rotates as the swing span rotates. This presentation allows the operator to visualize the position of the swing span relative to the fender and Bronx rest pier from above.

Electrical

The Madison Ave Bridge is an example of early 20th-century American engineering, embodying the Beaux-Arts architectural style, with its intricate design and functionality. Over the years, the Madison Avenue Bridge has undergone renovation and rehabilitation to preserve its structural integrity, upgrade its machinery and electrical system and adapt to the City’s changing transportation demands. The upgrade to the bridge's electrical power systems includes new equipment and wiring that ensures redundant power supply, dual programmable logic controllers with semi-automatic sequence control and interlocking of various electrical components.

There are three submarine cables connected to the center pier from both Manhattan and the Bronx. Before starting the rehabilitation, the insulation resistance of the Manhattan submarine cables was measured to assess their condition. The results indicated that the existing cables could continue to be used without the need for replacements or additions which had been installed in a previous rehabilitation project in the 1990s. Retaining these submarine cables offers significant benefits for both the infrastructure and the communities they serve, as they are essential for maintaining uninterrupted power and communication links between the two shores and the center span. Additionally, retaining the existing submarine cables leads to cost and schedule savings.

As the submarine cables enter the center post, they are terminated in submarine cable terminal boxes located at this point. These boxes are NEMA 6P stainless steel enclosures equipped with terminal blocks for cable connections. Designed to be submersible enclosures as a result of learning from experiences from Hurricane Sandy, the boxes feature water-sealed entries with Roxtec fittings. These fittings offer flexible sealing solutions for cable penetrations and certified protection against fire, gas, and water. Inside the submersible enclosures, the conductors are safely terminated and connected, intended to prevent potential electrical power failures from water ingress if it ever raises up to this portion of the center pier (as happened during Sandy). These boxes enhance the infrastructure's integrity and the reliability of the electrical power system.

The continuation of power connection from the submarine cable terminal boxes to the motor control center in the machinery room above the center post is facilitated via a collector ring. A collector ring is a rotary electrical interface that allows for the transmission of power between the stationary and rotating parts of the bridge. The benefit of using a collector ring lies in its ability to maintain reliable connections while accommodating the rotational movement of the bridge. This is achieved through a copper ring bus bar and brushes that ensure consistent electrical contact without concerns about cable twist and turning, which can be an issue in rotating systems. By employing this system, the connection remains stable and efficient, effectively addressing potential cable connection concerns. At the motor control center, an automatic transfer switch is installed to manage power sources from Manhattan and the Bronx. This switch automatically activates when it detects that the selected power source is not properly energized, ensuring an immediate transition to the alternative power supply. The setup, which allows power facilities from Manhattan and the Bronx feeding the center span via submarine cables, submersible enclosures, collector rings, and automatic transfer switch plays a crucial role in ensuring the redundancy and uninterrupted power supply of the bridge. This configuration guarantees that the electrical systems remain reliable and functional, even as the bridge rotates.

Power redundancy is not limited to the center span of the bridge but is also established at the gate houses on both shores. Normal power is supplied from Manhattan and the Bronx to the respective gate houses, while redundant power is provided via the submarine cable systems from the center span. The power is transmitted at 480 Volts in a three-phase system, which is then stepped down to a 208/120 Volts three-phase system in the gate houses using transformers. To ensure proper switching between normal power and the redundant power from the center span, a Kirk key interlocking system is implemented in the gate houses. This arrangement provides a layer of redundancy and ensures an uninterrupted power supply to the bridge gate houses, regardless of where the primary feed to the bridge is coming from.

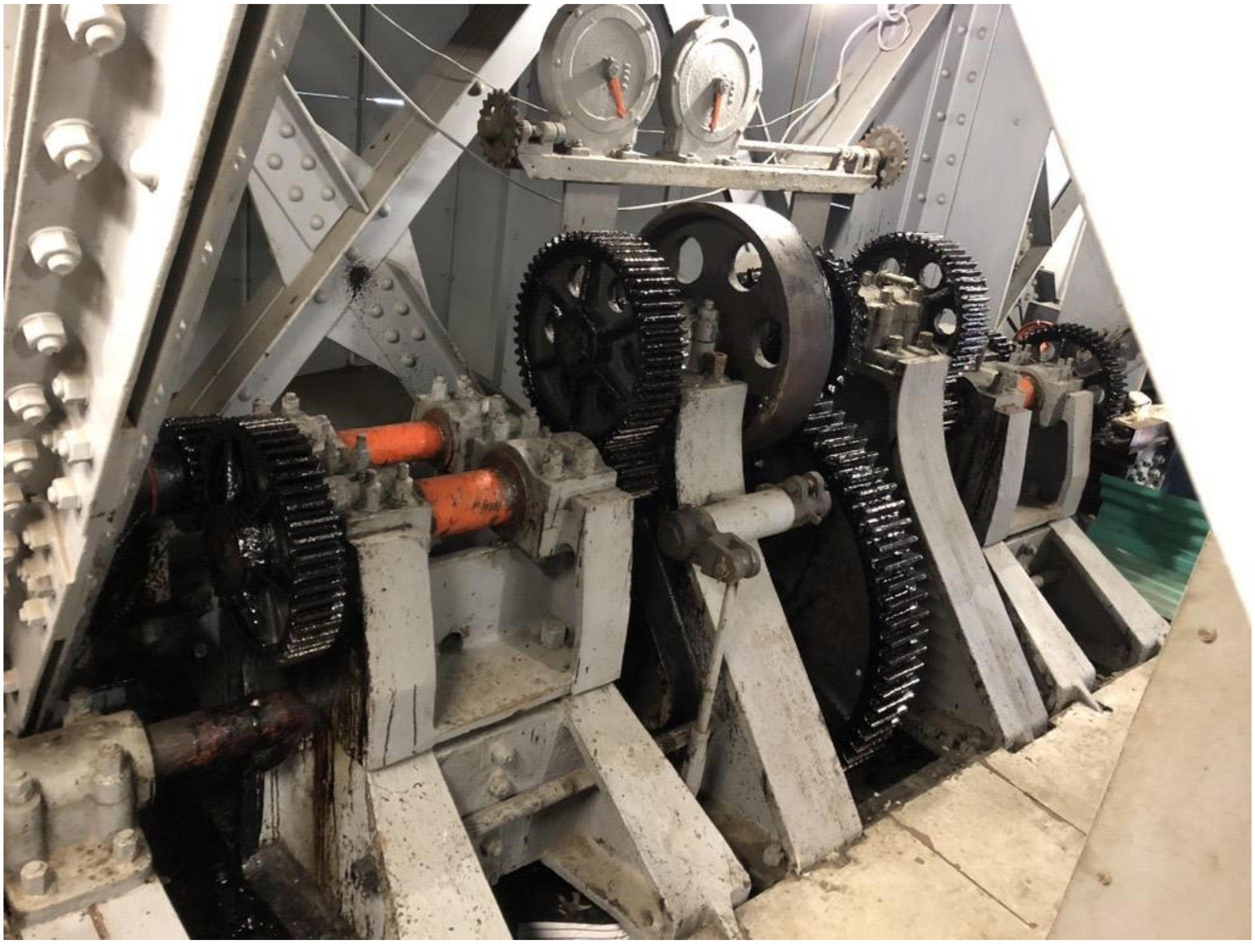
With the redundant power provided, a sophisticated control system has been implemented to ensure optimal operation of the bridge. This system features multiple layers of redundancy, including two programmable logic controllers, two flux vector drives, and two span drive motors for bridge rotation. The seamless transition between the programmable logic controllers allows for uninterrupted control in case of a fault. Redundant flux vector drives ensure that if one fails, the other can take over, maintaining span motor operation. Similarly, the dual span motors offer comparable redundancy. This system is further hardened as the programmable logic controllers incorporate interlocking mechanisms that prioritize safety by disengaging the end lift first, then the centering lock, and finally enabling the span motors. A similar interlocking process is used for closing the bridge. This comprehensive control setup ensures a highly reliable system, focused on proper and safe operation of the bridge’s rotation mechanisms.

The Madison Avenue Bridge stands as a pivotal engineering marvel and vital transportation link between Manhattan and the Bronx. Since its completion in 1910, this swing bridge has been a critical conduit for both vehicular and pedestrian traffic, exemplifying early 20th-century American engineering with its Beaux-Arts architectural style and innovative design. The bridge’s recent upgrades reflect a commitment to preserving its structural integrity and enhancing its functionality. With the integration of modern electrical systems, including redundant power supplies, advanced submarine cables, and robust control mechanisms, the bridge ensures a reliable and uninterrupted service. The sophisticated setup, encompassing everything from submersible enclosures and collector rings to automatic transfer switches and redundant control systems, guarantees seamless operation and safety even during rotational movements. These enhancements not only uphold the bridge's historical significance but also address contemporary demands, ensuring its continued effectiveness as a crucial infrastructure asset in New York City.

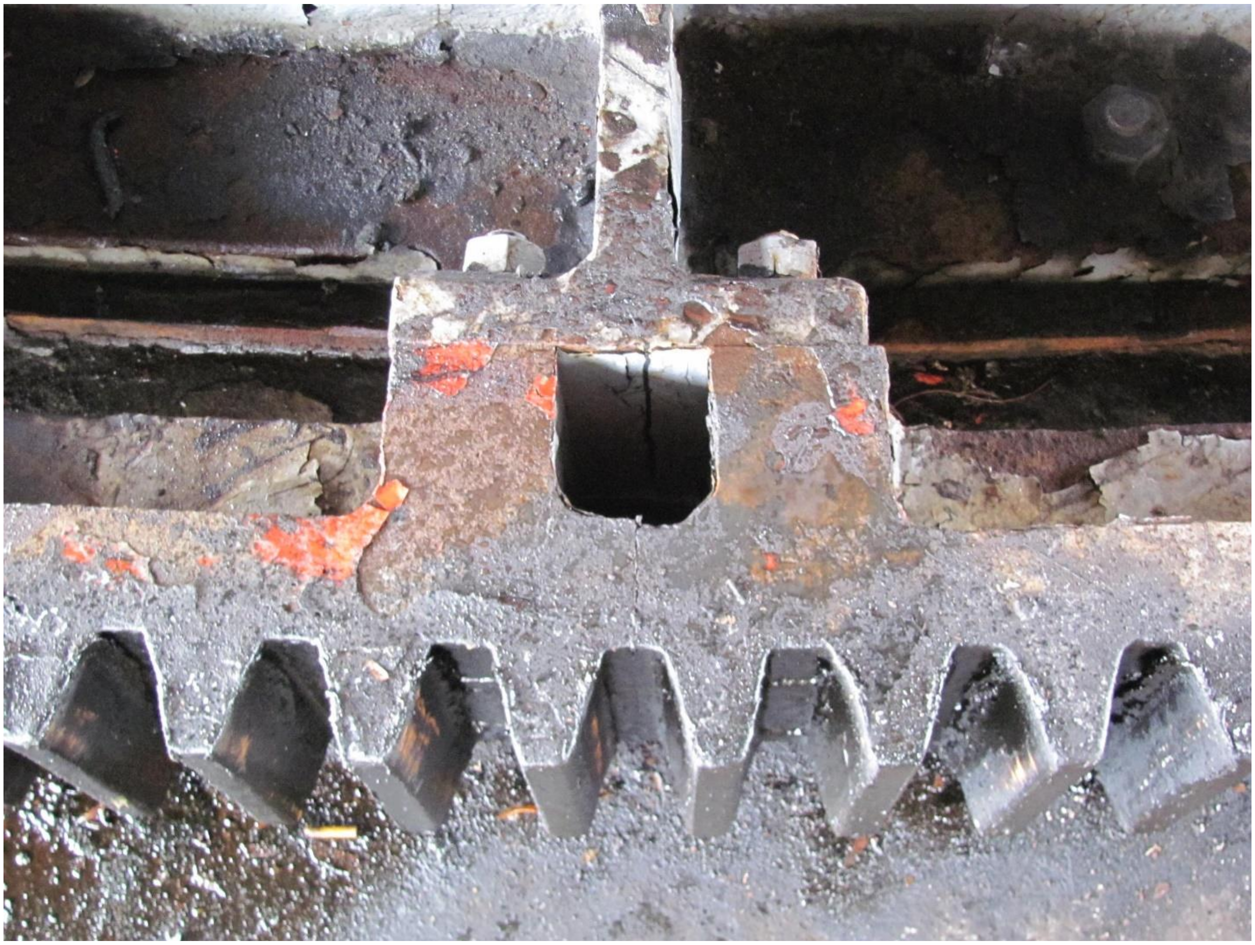
Acknowledgements

Owner	NYCDOT
Resident Engineer	H&H / Entech
General Contractor	SKANSKA
Electrical Contractor	EJ Electric
Machinery Fabricator	G&G Steel
Controls Supplier	Champion Controls
Hydraulics Supplier	Atlantic Industrial Technologies
Painting Contractor	Champion Painting
Traffic Gates	B&B Roadway

THE END


CAPTION: Existing span drive open gears which were replaced with enclosed gearing.

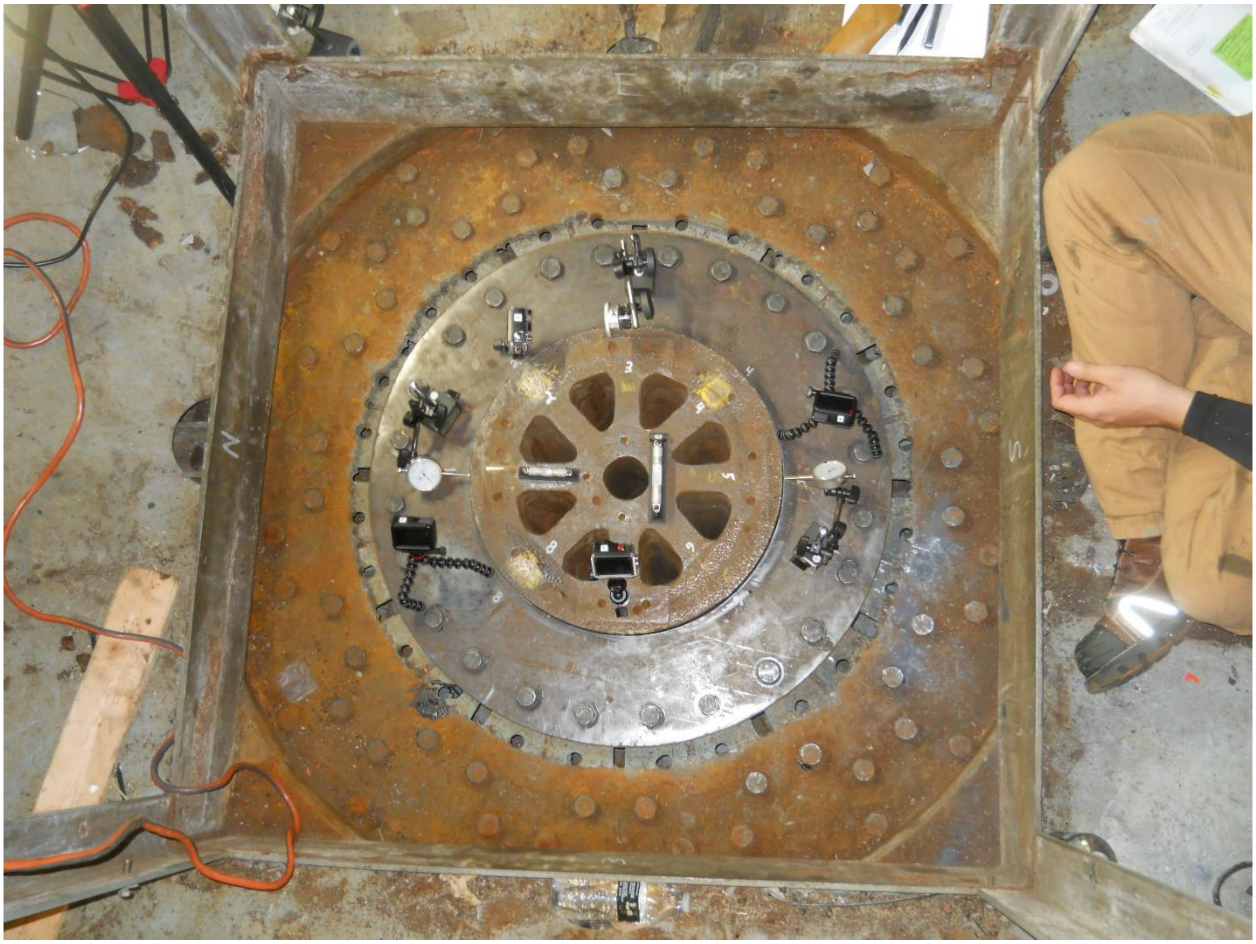
CAPTION: Existing south side of center pier.



CAPTION: Existing rack joint connected to the track chair using four T-head bolts.

CAPTION: Existing rack, north pinion and center pier with small platform at the pinion location and no railing.

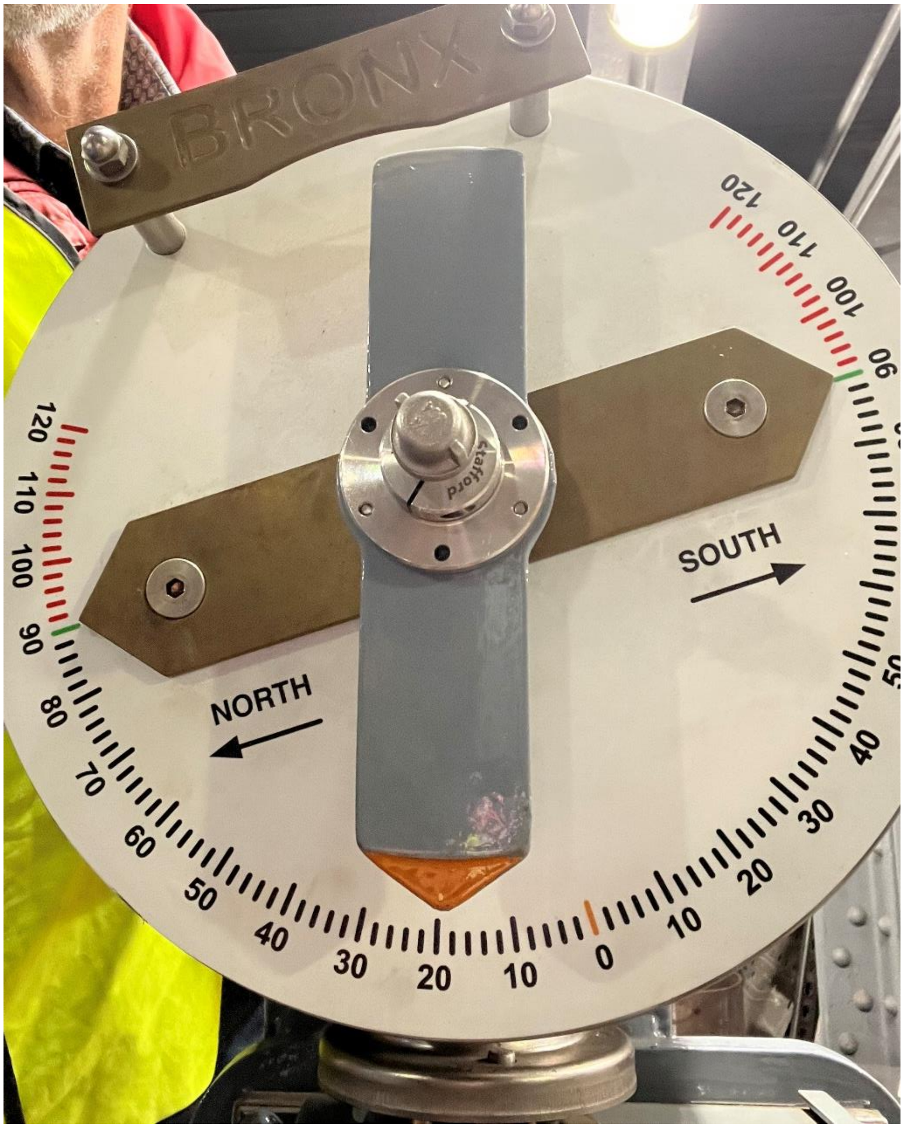
CAPTION: Machining device to machine the cylindrical surface of the center post. The device fits between the post and the ends of the 12 radial struts.



CAPTION: Looking down on the top of the center post after removal of upper gusset plate. Dial indicators are installed on the temporary plate to monitor the movement of the span in relation to the post as the span rotates. Two machinist’s levels are used to monitor any change in tilt of the center post.

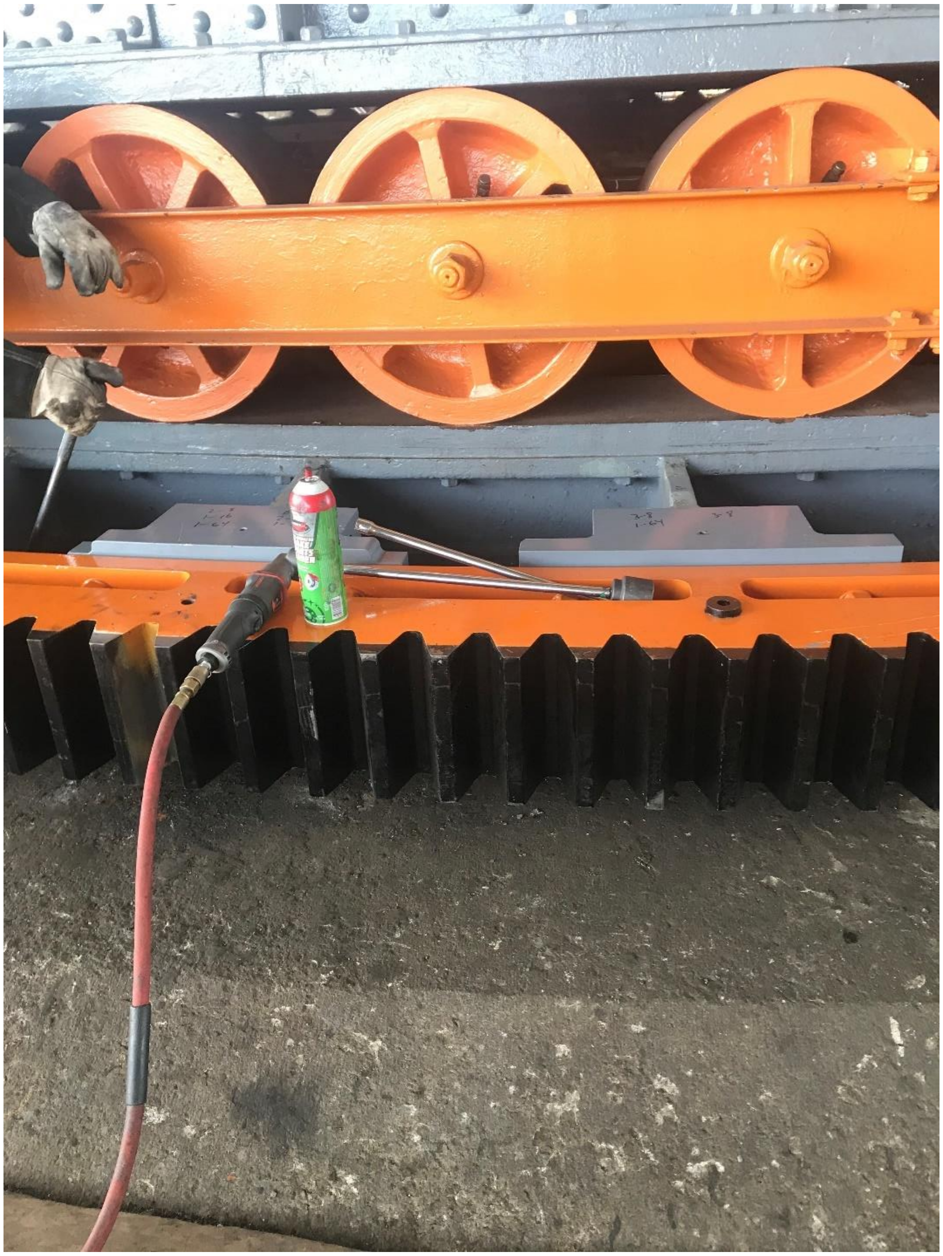
CAPTION: Removed portion of upper gusset plate which was replaced with a temporary plate to limit radial motion during test openings.

CAPTION: Existing rack, rollers, track chair, upper and lower tracks.

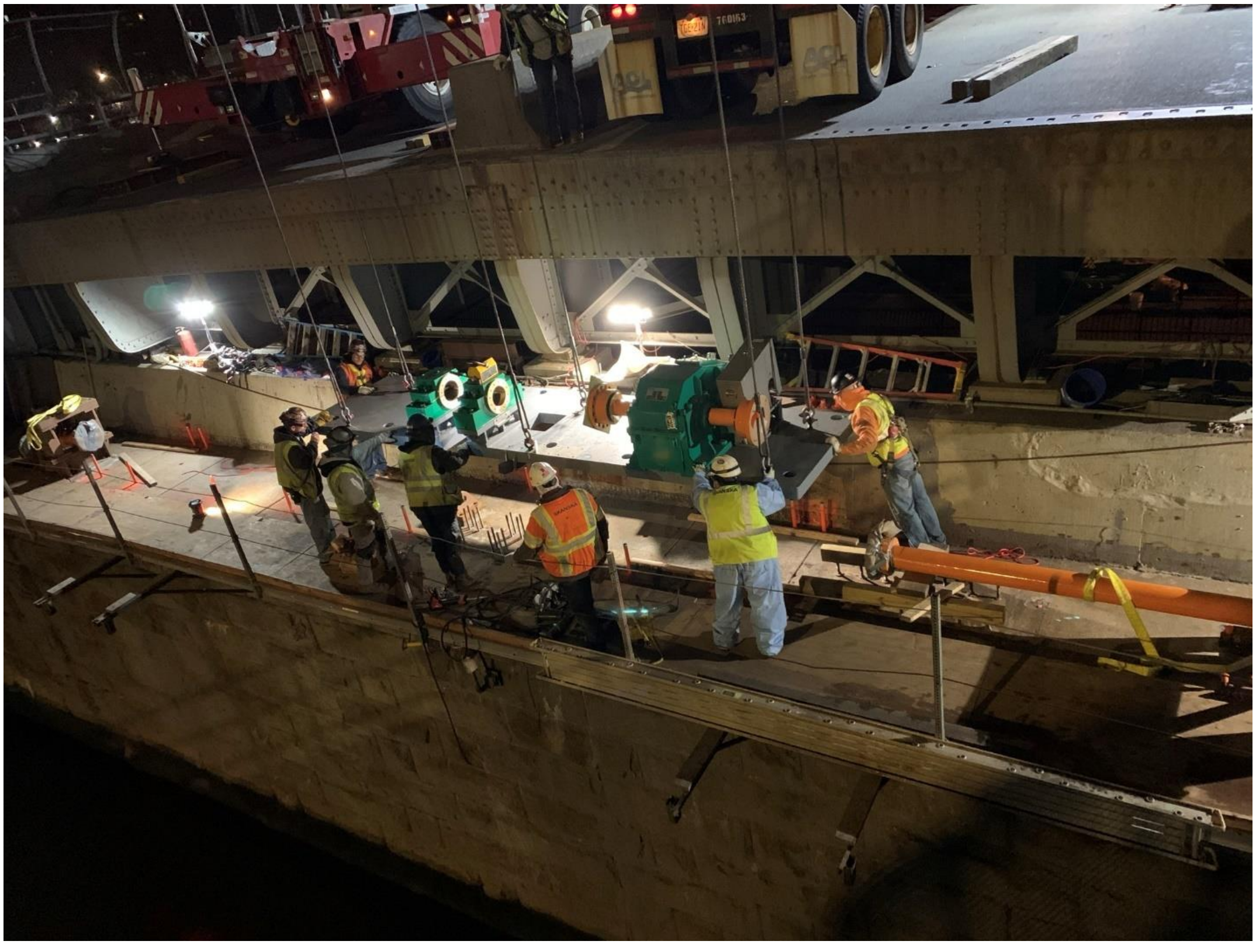


CAPTION: Position indicator grey pointer representing the swing span with orange tip pointing to the 20 degree clockwise angle of opening. The operator is oriented with bronze plates representing the fender and Bronx rest pier.

CAPTION: New south pinion in mesh with the rack. Pinion shaft, pillow block bearings, coupling and support are shown.

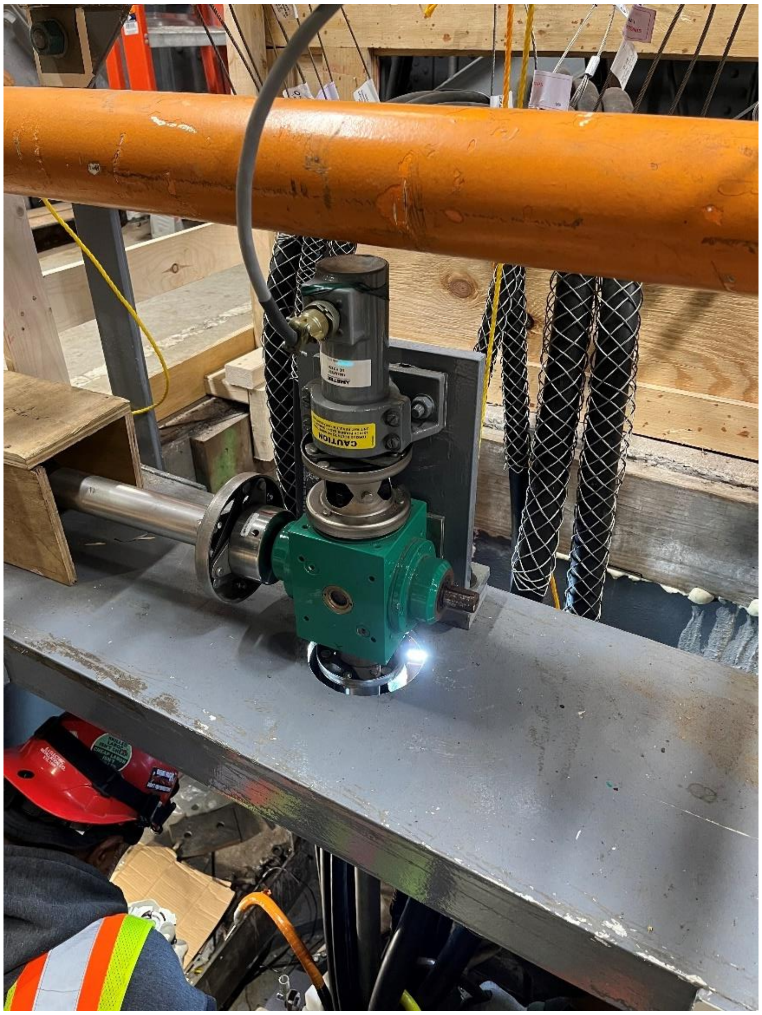


CAPTION: New rack installed on the existing track chair. The rack supports, pinions, rollers and tracks are visible in the background.



CAPTION: Installation of the end lift machinery mounting plate on the Manhattan rest pier. The north secondary reducer and bearings for the center truss end lift pillow block bearings.

CAPTION: New access platform around the center pier for maintenance and inspection of the rack, pinions, rollers and tracks.


CAPTION: Instrument drive reducer and encoder. The control cables in strain relief fittings pass through the collector ring.

CAPTION: Existing collector ring. Eight rings for 3-phase power from two sources. Instrument drive shaft and control cables pass through the center of the assembly.