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LOAD PATH REFORMULATION AROUND MULTIPLE RESTRICTIONS FOR AN INDUSTRIAL RETROFIT

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Process, operational, and electrical restrictions inherent in the design of a regulatory compliance upgrade for an industrial plant, and overburdened existing structure, required an unusual structural retrofit. There were multiple restrictions on placement of structural members and multiple needs for additional strength in the existing members. To manage the constraints, the load path was reformulated to bypass problem areas and focus upgrade work on just a few locations. The key in selecting upgrade locations was determining where there was reserve capacity in the existing foundation. Two such locations were identified and super-bents were formed there using existing moment frames. Horizontal trusses were built to bridge between the super-bents. A super-bent included a new grade beam, with end bulbs surrounding existing column pedestals, column section augmentation, new heavy anchor bolts and new diagonals to convert two parallel beams into a deep truss. Embedded structural steel was utilized in the grade beam end bulbs to distribute anchorage forces and develop reliable load paths around obstructed columns. Unusual uses of structural steel, work in obscured areas, unconventional structural systems and construction schedule interuptions led to an increase in construction management and inspection scope and complexity. CM lessons learned from the project involved better interaction of disciplines during design and greater input from engineering just prior to and during construction.

Keywords: Concrete, Grade beams, Embedded structural steel, Strengthening, Super-bent, Construction management lessons.

1 INTRODUCTION

Historically, the typical industrial pipe rack has comprised of a series of parallel moment frames or bents, each approximately 20 to 30 feet wide and one spaced from the next at about the same distance, resisting lateral load in the short (or transverse) direction, with bracing every few bent-to-bent bays resisting lateral loads in the long (or longitudinal) direction (Arya *et al.*, 1979). Typical pipe rack height is in the range of 15 to 30 feet. For racks built prior to 2001, when OSHA began requiring a minimum of 4 anchor bolts for columns (Safety Standards 2001), column anchorages often consisted of only two anchor bolts near the column center, meaning no significant moment resistance could be developed in the base connection. Further, anchorage capacity of older anchor bolt assemblages has been found by the author to usually have relatively little capacity computed according to the latest generation of strength formulas (ACI 318-02 2002).

One such pipe rack, the original construction drawings for which bear the date of 1981 (Figure 1), was to be retrofitted with new structure, equipment and piping installed on top of it as part of a regulatory compliance upgrade for the plant process unit. The added objects would increase wind and seismic load. That the retrofit would be on top of the existing framing would magnify the overturning effect of those loads. Further, it was likely that current code wind and seismic load provisions (ASCE/SEI 7-10 2010), especially when applied in conjunction with more modern insight on the effect of wind on industrial open structures (Wind Loads 2011), would lead to larger unit seismic loads and wind pressures and/or (for wind) effective tributary areas for all parts of the structure, whether original or retrofit.

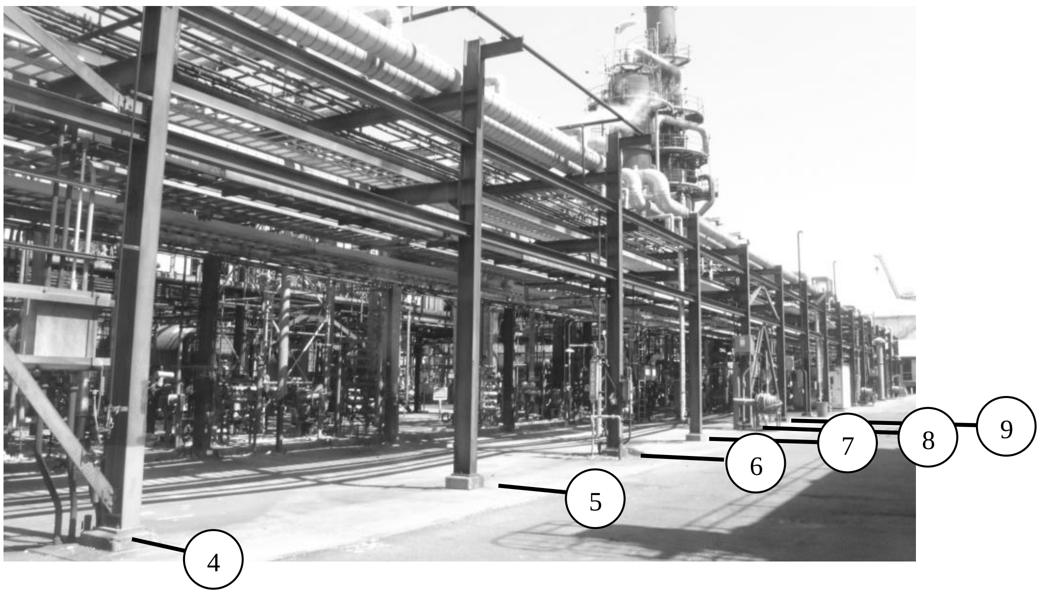

Figure 1. Pipe rack prior to retrofit.

Beside load effects, sources of challenges for retrofit design and construction were electrical, structural, piping and process constraints and construction management demands. To overcome these, the load path for the transverse direction of the pipe rack had to be reformulated relative to the typical concept for such structures.

2 LOAD PATH REFORMULATION CONCEPT

2.1 Analysis of Existing Structure

As originally designed, the moment frames had to be self-sufficient relative to transverse forces. Each moment frame must support the gravity and transverse lateral forces tributary to it. There is no means for redistribution of these loads to adjacent bents. Thus, if the moment frame capacity were inadequate, each and every moment frame would, keeping the original load path concept, have to be strengthened.

And it was indeed found that the bents, once the new loads were applied, were inadequate. Analysis showed that the two-bolt column anchorage could not meet demands. Frame members were shown to be overstressed. Story drift was too much.

2.2 Load Path Constraints

Under most columns, the foundation comprised three "composite" piles: driven timber pile topped by a cast concrete column stub. The lateral capacity of these piles was indeterminate and considered unreliable at any rate.

Foundations under columns to which a vertical, longitudinally oriented brace was attached, though, were more substantial: four 12-inch diameter steel piles. These foundations were designed primarily to react against load in the longitudinal direction. Therefore, they had considerable capacity for transverse lateral loads beyond the tributary load for a single moment frame.

Strengthening of column anchorages would have required enlargement of the concrete pedestals on which the columns rest, additional base plate and more anchor bolts. This rather involved proposition, which would have to be employed at every column of every bent, was deemed impractical from a schedule and construction cost standpoint.

Further, some of the columns rested not on an isolated pedestal but a corbel integral with a wall of an underground tank. Plant operations did not want to apply further loads or add structural elements to this wall due to concerns over its structural condition. Moreover, there were any number of pipes, machines and instruments that could not be moved which prevented access to concrete in the area to which additional anchorage elements would have to be affixed.

It was proposed to add bracing in the lower "story" of each moment frame. This would take care of the overstress of the frame members but not the anchorage inadequacy. However, bracing was disallowed by plant operations because it would prevent passage of maintenance vehicles down the "hallway" of the pipe rack.

Consideration was given to adding plates to flanges of beams and columns in order to increase strength and stiffness. The amount of plate required, though, was so great as to be impractical from the standpoint of material cost, weld placement and constructability. Constructability problems stemmed not only from handling heavy pieces but also from having to work around multiple and frequent blockages of access to structural members by electrical conduit, cable tray, instruments and piping that are typically clustered around and supported off of structural columns rather than separate, dedicated vertical support members.

The attachment of WT sections to the faces of wide flange beams and columns was considered as well. They required less free surface area of column and beam flanges but nevertheless, there were still too many items attached to members to allow this to be feasible.

2.3 Super-Bents

In order to satisfy the above noted constraints, the only feasible approach perceived, short of building a whole new, separate structural system, was to turn two existing moment frames into super-bents that would collect essentially the entire lateral load applied to the area where the new regulatory compliance infrastructure was installed. The bents selected were ones whose columns sat on steel pile-supported foundations so that there would be sufficient foundation lateral capacity. A rendering of the structural model of the retrofit super-bent structural system is shown in Figure 2. The super-bents are on column grid lines 3 and 9.

2.3.1 *Bridge trusses*

To affect the super-bent system, a number of structural retrofits were required. One of these was means to collect transverse lateral loads otherwise tributary to typical moment frames and deliver them to the super-bents. To do this, two horizontal trusses were added to the structure. The lower of the two (Figure 2) was composed of new steel threaded in amongst the existing framing. To avoid conflict with and disturbance of the existing framing, the chords of the lower truss were set outside the footprint of the original pipe rack. The upper bridge truss was composed entirely of new framing.

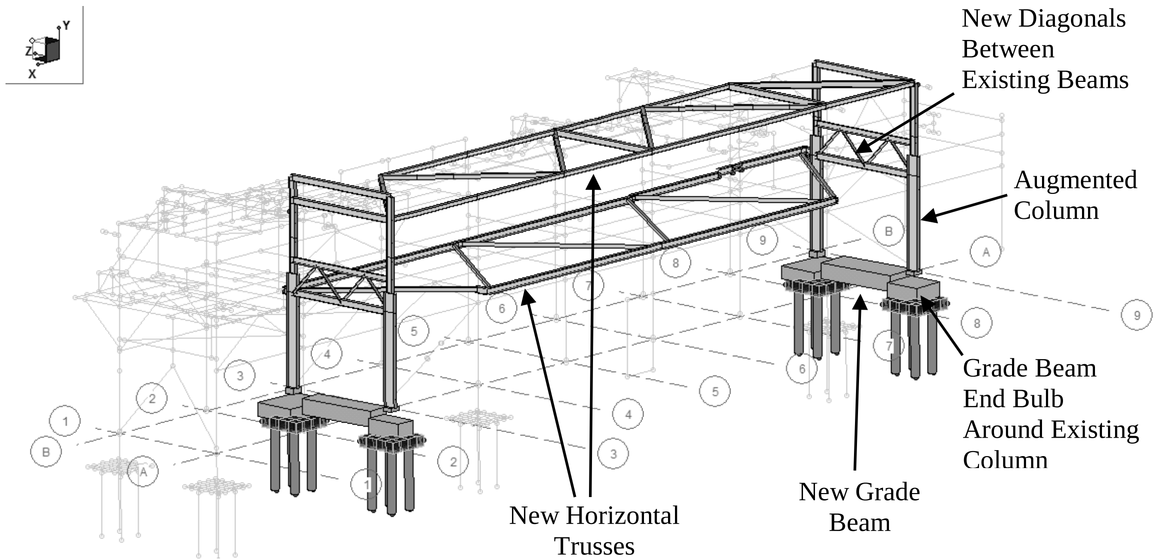

Figure 2. Super-bent structural model (with essentially same viewpoint as in Figure 1). Note, members not part of the super-bent system appear as faint wireframe elements.

2.3.2 *Frame strengthening*

The superstructure framing of the super-bents had to be strengthened in order to support the lateral load. This strengthening comprised three main aspects:

(1) Diagonal elements were added to the space between two existing parallel beams in order to form, a stiff, deep truss. The diagonals were placed without interfering with existing piping.
(2) Most of the height of the original columns was augmented with WT spines welded to the outsides of the columns. The outside faces of the columns at the super-bent locations were essentially free of obstruction. With the spines, the columns as strengthened were double the depth of the original columns.
(3) Anchorage capacity was added to the columns such that the base connections would be moment-resisting.

2.3.3 *Foundation strengthening*

It was determined that the steel pile groups had sufficient strength to resist the applied lateral loads. However, the existing foundation system did not have enough moment capacity to develop a moment-resisting reaction at the bases of the columns. To address this, a concrete grade beam was added between the two columns of each super-bent. The beam was tied into the column anchorage assemblage in order to transfer moment but surrounded the existing pedestals with such girth that only minimal strain could be developed in the pedestal before the grade beam-column interaction arrested joint rotation. Thus, moment was effectively prevented from transferring into the pedestal-pile cap-pile assemblage.

3 COLUMN-TO-GRADE BEAM DETAILING

One final constraint affecting the retrofit structural system concerned the presence of a vertical duct bank extending up alongside some of the super-bent pedestals. It was required by plant operations that the duct bank not be touched in any way. Therefore, the grade beam could not follow a direct path between the two columns of a bent. In essence, stresses had to “turn” several corners and “go around” the duct banks to transmit column base moments into the body of the grade beam. This is illustrated in Figure 3.

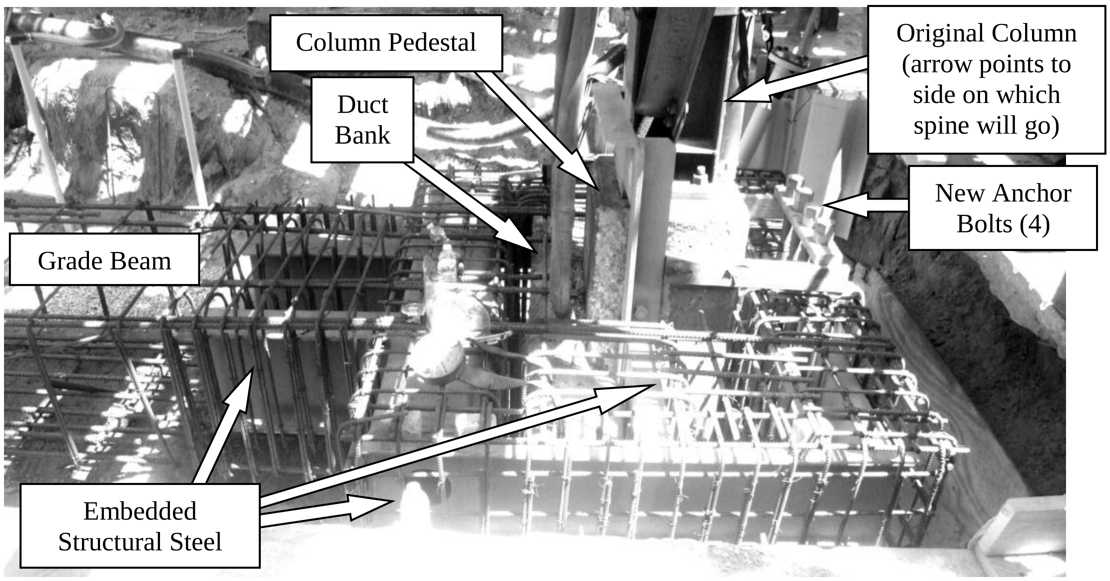

Figure 3. Super-bent grade beam on column grid line 3, looking along grid line B towards line 2. Note, column spine not yet installed.

To direct stresses through the concrete grade beam bulb surrounding the existing column and stabilize stress transfer around the duct bank, structural steel was embedded within the bulb and enclosed in ties. This included a pair of channels at the back or outside half of the bulb, against which the new anchor bolts could bear and with which anchor bolt forces could be reliably distributed into the rest of the bulb. Usual limit states for cast-in-place anchor bolts, except for steel tension failure, were considered not applicable in this case.

To design the embedded structural steel, an analysis was done with only the steel in the model, no bulb concrete. The steel had to carry all the load. Then, for checking lateral drift, the analysis was repeated with the bulb concrete included in the model. The embedded structural steel was continued into the main body of the grade beam far enough for grade beam longitudinal rebar to be developed.

4 CONSTRUCTION MANAGEMENT LESSONS LEARNED

The structural detailing concrete as well as embedded steel and the superstructure around the column and column pedestal, was unconventional and, more pointedly, awkward. It was important that construction management activities involve not just routine inspection personnel and schedule. The engineer of record needed to perhaps not continuously inspect the work but did need to frequently and regularly inspect the construction work and communicate with field personnel. It is important that both engineering and construction management personnel insist on this high level of field observation through to the end of the project. There is a tendency to bypass detailed observation as the project progresses and a sense of familiarity is developed. However, not one grade beam bulb was completely identical to any of the others so familiarity can be misleading, and the sense of familiarity should always be held suspect.

The principals of frequent inspection by the engineer of record and engineering-construction management communication holds as well for superstructure installation where details are unusual, especially as they are made so by construction scheduling. A case in point was one of the column spines. Some electrical conduit interfered with the spine. The conduit was scheduled for relocation regardless of structural work but could not be worked on until the turnaround for the process involved. Therefore, the spine had to be installed in three pieces; two prior to turnaround, one after. This odd detail was well known to engineering who had been intimately involved in developing it and making sure it would be structurally effective. But by the time the last piece of the spine could be installed, it had been forgotten and was left out—engineering had not been involved enough in construction inspection.

5 CONCLUSIONS

(1) Key to managing major structural strengthening is establishing a suitable load path.

(2) The first task is to determine availability of reserve foundation strength. Every effort must be made to exploit excess foundation capacity before resorting to requiring new foundations or major foundation strengthening.

(3) As in the case at hand, a likely source for excess foundation capacity needed for lateral load in one direction is a foundation relatively lightly loaded in that direction but designed for large lateral loads in the other direction.

(4) Once sources of sufficient foundation strength are identified, if they can be identified, the superstructure must be configured and strengthened to transmit loads to the new foundation locations. Load path reformulation will likely be necessary. The load path reformulation scheme ultimately selected will be sifted out from among several possibilities by the various spatial, process, structural, electrical, instrumentation and mechanical constraints presenting.

(5) Close and frequent field observation by the engineer of record and contact between the engineer of record and the construction management team and contractor must be insisted on and carried out when load path reformulation is unconventional, whether due to structural configuration, schedule or both.

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