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EVALUATION AND RETROFIT OF PETROCHEMICAL FACILITIES

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ABSTRACT

At present, there are no guidelines or code documents for seismic evaluation and retrofit of industrial facilities, including petroleum refineries. Many of these facilities in California and along the Pacific Rim are in areas of high seismicity. These facilities contain environmentally sensitive materials, and are typically of older construction stock, thus overall seismic risk is sizable. Currently, philosophies for analysis and retrofit of typical refinery structures vary widely. This paper will present the philosophy, methodology, and criteria developed for assessment and retrofit at Chevron Corporation facilities. It incorporates concepts designed to minimize risk both on a global level at the facility, and at the local level with the structure. Prudent risk management and risk analysis techniques are also incorporated. Pitfalls and special considerations that apply to these particular types of structures are discussed. The techniques adopted for refinery structures could also be extended to other similar types of industrial facilities.

KEYWORDS

Petrochemical; retrofit; refinery; risk management; analysis; seismic

INTRODUCTION

This paper describes key issues and lessons learned from the implementation of a seismic evaluation and retrofit program by Chevron USA Products Company. The scope of this program includes two California refineries, a Salt Lake City refinery, and marketing facilities in California, Oregon, Washington, Utah, and Idoho.

Chevron's seismic assessment and retrofit program was initiated in 1989, prior to the Loma Prieta earthquake, as part of the Chevron Corporation's overall risk management plan. The goal of this program was to identify and reduce seismic risk in Chevron's West Coast facilities. Chevron's risk management philosophy is one of proactive risk reduction, hence, a program of this type is consistent with the company's overall risk management program. The Loma Prieta earthquake presented a unique opportunity to implement this program.

Implementing a seismic assessment and retrofit program in a petrochemical facility was a technically challenging project. In contrast to buildings, no accepted industry standards or guidelines for the assessment and retrofit of industrial facilities existed at the time of program inception. Since petrochemical facilities contain numerous unique structures, a considerable amount of engineering judgment was required in the evaluations process. In addition to the need for an assessment criteria, a system for prioritizing the seismic vulnerabilities of the assessed structures was needed. Finally, once the vulnerable structures were prioritized based on risk, retrofit criteria were needed to upgrade the vulnerable structures.

This paper focuses on some unique technical issues from the retrofit phase of Chevron's seismic hazard mitigation program. However, some background information regarding the assessment methodology and results are presented to give the reader a better understanding of the program. For more details regarding the assessment methodology, the reader is referred to Summers and Wesselink (1994).

ASSESSMENT

The assessment approach consisted of several key steps:

1) Investigation of site specific hazards and development of site specific ground motion
2) Identification of critical structures for assessment
3) Comparison of structure ultimate strength versus expected earthquake demand
4) Prioritization and ranking of vulnerable structures based on seismic vulnerability, consequence of failure, and business needs

Site Specific Response Spectra

A site specific response spectrum was used for the evaluation of the structures under consideration. The hazard used as the basis for the evaluation was generally an earthquake with a 10% probability of exceedance in 50 years, or a return period of 475 years. This level of hazard is used in the State of California's Risk Management and Prevention Program (RMPP) for assessing facilities containing acutely hazardous materials (AHM's). This is also the level of hazard currently used for the design of new facilities.

Different levels of hazard may be chosen as the basis for an assessment in certain situations, e.g., the level of hazard can be chosen based on the remaining life of the structure. FEMA-178, "Guidelines for the Assessment of Existing Buildings", (FEMA, 1992) effectively uses 85% of the 475 year return period earthquake response spectrum as the basis for assessment of existing facilities. This level of hazard corresponds to a 10% chance of exceedance in 30 years, or a return period of approximately 250 years. Similarly, if a structure is critical to safety, functionality, or profitability of a facility, a higher level of hazard may be chosen for the assessment. In voluntary upgrade programs, the level of hazard selected is usually a direct reflection of the owner's risk tolerance.

Assessment Criteria

For the assessment of plant facilities, Chevron used a guideline document developed by the RMPP Seismic Guidance Committee (1990, 1992). As noted above, this document was developed for the assessment of facilities containing acutely hazardous materials. While most of the structures in petrochemical facilities fall outside this classification, this document was felt to be the most appropriate guideline because it specially applied to existing petrochemical facilities.

The structures were evaluated using the RMPP Guidelines (1992) and sound engineering judgment. The key step of the evaluation process was to determine the return period of the earthquake that was representative of the ultimate capacity of each structure. To do this, site specific response spectra were developed for return periods of 25 to 475 years.

After determining through analytical evaluation which structural elements did not meet the specified performance level, i.e., having an ultimate strength corresponding to a 475 year return period earthquake, the deficient structures needed to be ranked and prioritized according to their level of seismic risk. The following priority matrix was developed for this purpose.

Table 1. Risk Analysis Prioritization Matrix

Criticality of Facility Function	Earthquake Return Period of Weakest Structural Element at Ultimate Capacity			
	< 100 Years	100-250 Years	250-475 Years	>475 Years
High	1	1	2	3
Low	1	2	3	3

The priority codes of 1 (critical), 2 (undesirable), and 3 (acceptable) were assigned to aid in the retrofit planning effort. Obviously, structures with a priority 1 rating were of the highest risk and were targeted to be strengthened first.

GENERAL RETROFIT CONSIDERATIONS

Retrofit Objectives

Setting objectives for structural performance is the key to defining retrofit criteria. Chevron's approach was to set a goal of no structural collapse for its criteria, so as to avoid environmental release or fire related problems. Simply, the goal of the retrofit was to prevent any structure from a catastrophic failure, while realizing that some limited damage could occur. It is important to note that the intent of the program was not to ensure current code compliance, but rather to meet the selected performance objective. Definition of retrofit objectives is a direct reflection of the risk tolerance of the facility owner.

Strengthening Criteria

In contrast to the design of new facilities, there are no code documents addressing retrofit of petrochemical facilities. Chevron used a modified version of a guideline document developed by the RMPP Seismic Guidance Committee because this document was felt to be the most appropriate guideline. The acceptance criteria used in the RMPP document is:

$$D + L + \frac{E}{Q} \leq C \tag{1}$$

where D = dead load; L = live and/or operating loads; E = earthquake load; Q = ductility based reduction factor; and C = capacity. The RMPP criteria was modified in the following manner. In the RMPP document, Q is used as a ductility factor. A spectral factor, F, was developed to replace Q, and was defined as follows:

$$F = Q \qquad \text{for } T \geq 0.5 \text{ sec.} \tag{2}$$

$$F = \sqrt{2Q-1} \qquad \text{for } T < 0.5 \text{ sec} \tag{3}$$

where T = fundamental period of the structure. This procedure was adopted from Newmark and Hall (1982) for developing inelastic design response spectra from elastic response spectra. This procedure accounts for the reduced ductility in the energy controlled portion of the response spectrum.

Drift criteria also requiried consideration. At the time, there was no guidance on acceptable drift limitations for refinery structures. As a result, considerations based on functionality and stability of each structure were used to judge acceptibility.

The key philosophy of the strengthening criteria was to ensure that the proposed retrofit solution would maintain a ductile structure. Strengthening a component of the structure that is currently weak but ductile could force the failure into other components which could be brittle. Simply, a structural element that is weak, but has a ductile failure mode, should not be strengthened to the point where the failure mode becomes a brittle one. An example of this would be a process column on a steel support skirt where the anchor bolts were found to be under capacity. The addition of too many additional anchor bolts could force the failure mechanism from stretching of the anchor bolts, a ductile mode, to buckling of the support skirt, a brittle one.

Input Motion

Site specific response spectra were developed for each major facility that was assessed as part of this program Response spectra with return periods of 25 to 475 years were generated so that various levels of desired performance could be addressed. As discussed earlier, different structures could be retrofitted for different hazard levels depending on their function, criticality to operations, etc. In most cases, a hazard level of 10% chance of exceedance in 50 years, i.e., a 475 year return period, was selected as the desired level of performance. However, a hazard level of 10% chance of exceedance in 30 years would be considered reasonable.

SPECIFIC CONSIDERATIONS FOR TYPICAL STRUCTURES

Petrochemical facilities contain many unique structures that are unlike typical building structures. Accordingly, retrofit solutions for petrochemical structures are typically unlike building retrofit configurations. During the course of the seismic assessment and retrofit of the facilities, several types of petrochemical structures required special consideration and use of engineering judgment. These are discussed below.

Tanks

Seismic assessment and retrofit of tanks was distinctly different from that of other petrochemical structures because of the tank's shell type construction and the dynamic effect of sloshing fluid. Assessment was focused on two major areas, (1) the overturning stability of the tank during earthquake shaking, and (2) the potential interaction effect between attached piping and other appurtenance due to tank movement. An anchored tank was generally considered adequate when anchorage details are properly designed.

Seismic assessment of an unanchored tanks was generally conducted using the methodology presented in API 650 Appendix E (API, 1993). API 650 checks the overturning stability of the tank, with the overturning moments including both the contents moving in unison with the tank, and the portion of the contents that is sloshing. The resisting moment includes contributions from the tank dead load and the weight of contents adjacent to the shell. Past experiential studies and observation from past earthquakes indicate that the API formula substantially underestimates the resistant moment. However, it was the basis of current design practice, and was used for the initial tank check.

An existing tank failing to meet API 650 criteria was re-examined using the method developed by George Manos (Manos, 1986). Unlike API's approach, Manos' method calculated the resisting moment of the tank based on an allowable stress that maintains tank shell buckling stability. It also accounts for foundation deformability. The overturning moment is calculated similar to that of the API methodology with some simplification. In general, this method will allow a higher Safe Oil Height (SOH) than will API 650 Appendix E, except for tanks with thin shells constructing of high strength steel.

When an existing tank was found to be inadequate by both methodologies described above, several retrofit options were considered. A simple retrofit option was to lower the fill height of the contents. However, sometimes this was impractical due to operational requirements. If the fill height of the tank was random in nature, taking a statistical approach was used to establish the operating height. If the full existing fill height was needed for operational reasons, the tank was generally anchored in accordance with the provisions specified in API 650. Also, increasing the shell and /or annular ring thickness was considered. An innovative retrofit solution that was developed was stiffening the tank base by using a concrete slab such that the contents carried by the slab would serve as additional weight in calculation of the resisting moment.

Process Columns

Tall process columns are structures common to most petrochemical facilities. They typically consist of a thin shelled superstructure supported on a steel skirt and anchored to an octagonal pedestal foundation through anchor bolt chairs. The most common problem noted during the assessment was overstressing of anchor bolts. Anchor bolt tensile forces F_t were calculated with the following equation:

$$F_t = \frac{4M}{ND} - .85\frac{W}{N} \tag{4}$$

where M = the earthquake base moment; N = Number of existing anchor bolts; W = Vessel weight; and D = Bolt circle diameter. Typically, shear and tension interaction effects were not considered when determining the tensile capacity of the existing bolt. This assumption was made on the basis that the bolt with the maximum tensile force due to overturning would not resist shear due to the lack of local stiffness in the skirt. Figure 1 shows that the stiffer areas of the skirt will resist the base shear while the bolts receiving the maximum tensile force will resist little if any shear. In addition, friction between the base ring and the pedestal will further reduce the shear forces resisted by the bolts.

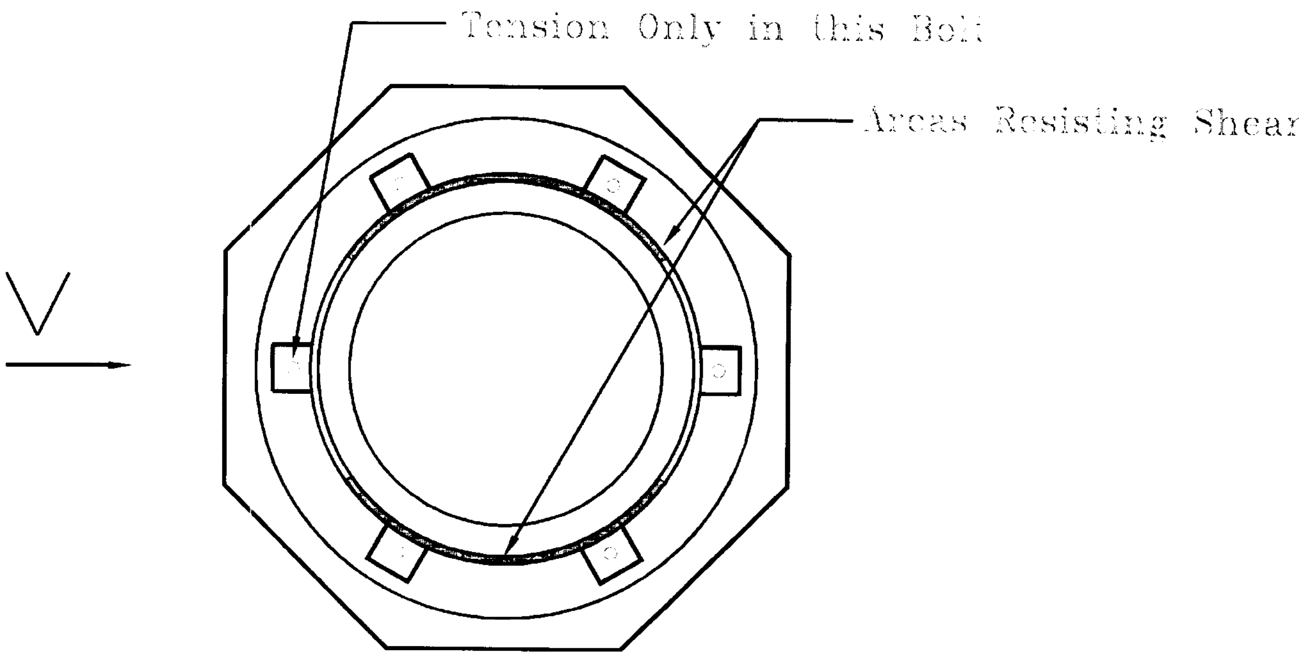

Fig.1. Plan view of typical support skirt showing areas of lateral shear resistance.

The most typical retrofit solution in this case was to add additional anchorage capacity through the addition of epoxy anchors. However, there were several key factors that needed to be addressed in the sizing and detailing of the additional bolts. The first dealt with the number of bolts added. Anchor bolt yielding is a ductile failure mode. Care was taken such that the moment capacity of the strengthened anchor bolt group did not exceed the flexural capacity and stability limit of the support skirt. If the flexural capacity of the bolt group exceeded the capacity of the support skirt, the resulting failure mode would be skirt buckling, a non-ductile one. Two additional checks on the new anchors were performed. They consisted of (1) checking that the bond strength of the epoxy anchor exceeded the yield capacity of the new bolt, and (2) checking that the flexural capacity of the pedestal foundation exceeded the expected flexural demand. These checks ensured that the anchors would not pull out before allowing the bolts to yield and that the concrete pedestal had adequate strength to transmit the expected loads to the foundation.

A final note on process columns is that dynamic analysis is recommended to calculate the expected loads at the anchorage as conventional static analysis will often result in overly conservative design forces. Overturning stability for tall columns was evaluated using an energy balance method. A more detailed discussion of this technique is discussed later in the foundations section.

Air Cooled Heat Exchangers (Fin Fans)

Air cooled heat exchangers, commonly know as fin fans, are usually located either atop elevated pipeways or at grade. During the assessment and retrofit design process, several key factors were identified. The first is that the structural support of fin fan units is integral to the mechanical components, and as such, is usually designed by the equipment vendor. It is typically installed as a "black box" with little consideration by the structural engineer. As a result, the integral fin fan structural support was often under capacity, or was poorly detailed. The most common example of poor detailing was eccentric knee braces to the support columns. The second consideration was the relationship between the rotational period of the fan motor and the fundamental period of the retrofitted fin fan unit. As a rule, the period of the retrofitted structure was kept outside of a +/- 20% margin from the rotational period of the fin fan motor. This was meant to insure that resonance or excess vibrations would not be induced into the structure during normal operations. The final consideration for fin fans dealt with units sitting atop elevated pipeways. Depending on the mass and frequency ratios of the fin fan unit to the supporting pipeway, the combined structure was modeled analytically so that amplification due the raised height could be accounted for in the design of the structural retrofit.

Elevated Pipeways

Petrochemical facilities commonly contain large elevated pipeways used to support process piping running throughout the facility. Since most pipeways are designed for loads larger than they actually support, a question is raised as to what should be the dead load considered for the seismic assessment and possible retrofit of the pipeway. Typically, pipeways are designed using a lumped mass assumption at each horizontal level. Using this assumption is very conservative in almost all cases for the following reasons. First, the damping effects of multiple pipes and the reduced load delivered to the structure due to sliding of the pipes is ignored in the analysis. A non-linear analysis conducted by Chevron, modeling multiple sliding pipes with various friction coefficients, indicated that actual loads induced into the pipeway structure can be on the order of 20 to 50 percent lower than those assumed by the "lumped mass" loading assumption. The second consideration is that the support offered by pipe "branches" attaching to adjacent process equipment is ignored in the analysis. In reality, the pipe branches will act to support the pipeway structure. This effect, however, is generally not considered in current engineering practice. Further study may be warranted.

Drift was also a factor to be considered in the retrofit of pipeways. Typically, drift limits were relaxed to h/250, subject to compatibility with attached piping or equipment, and stability concerns, as opposed to the building code limits of $.005h_x$ (ICBO, 1994).

Furnaces

Large, box-type furnaces are found in most petrochemical facilities. They typically consist of a steel support frame and steel panel walls surrounding the firebox. In general, the steel support frames were found to be adequate to resist the desired seismic loads, and few furnace retrofits were required. In situations where the steel support frame was found to be under capacity, consideration was given to the strength of the steel infil panels. The strength of these panels is typically not considered in the structure design, but represents significant reserve strength.

Foundations

Except for certain type of structural systems, foundations in petrochemical facilities are similar to typical building foundations. These types of foundations normally are fairly straightforward to assess. A particular type of foundation that presented some questions was the octagonal footing supporting tall columns. Using the conventional static force approach, this type of foundation often appears to have overturning stability problems, or exceeds the allowable soil bearing pressure.

These problems are largely due to overconservatism in the assessment methodology. From past earthquake performance data, and nonlinear time history analyses that have been performed internally by Chevron, dynamic instability rarely occurrs. Analysis results showed that for a typical tall vertical vessel, the maximum inertia force acts for only very short periods of time and reverses direction before overturning of the entire structure can occur. As a result, using static forces for overturning stability analysis or soil bearing pressure calculations could be very conservative

A more realistic approach for evaluating the seismic stability of existing structures for seismic stability is to use a safety factor of 1.0 against overturning , and 1.5 against sliding. However, a dead load reduction to 0.9D should be included to account for the vertical component of the earthquake. Alternatively, an "Energy Balance" can be used for the stability check. This method checks if the potential energy required to overturn the structure exceeds the imposed kinetic energy caused by the earthquake. Using this more realistic approach, very few existing foundations actually needed to be retrofitted.

CONCLUSIONS

Petrochemical facilities have several unique structures that require special considerations for their seismic assessment and retrofit. In addition, due to the lack of specific guidelines for the assessment and retrofit of petrochemical facilities, sound engineering judgment is a necessary element of a successful program. Finally, the use of performance based criteria is advised since it allows the owner to dictate the level of risk that it is willing to assume. This allows for the most efficient use of capital moneys, and provides for effective reduction of seismic risk.

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