A CASE STUDY CONSIDERING A 3-D PUSHOVER ANALYSIS PROCEDURE

W. Huang[1] **and P. L. Gould**[2]

[1] *KPFF Consulting Engineers , Los Angeles, CA, USA*
[2] *Professor, Washington University, Saint Louis, MO, USA*
Email: whuang@kpff-la.com, pgoul@seas.wustl.edu

ABSTRACT :

This paper concerns a unique failure during the 1999 Kocaeli, Turkey earthquake. With an unusually large rectangular duct opening located about 1/3 of the height above the base, a 115 meter high reinforced concrete chimney collapsed during the earthquake while several other similar structures survived with only moderate damage. Debris of the failed stack cut many lines, which fueled fires that shut down the refinery for months. This case study provides intriguing results, considering that the stack was designed and constructed according to international standards and is representative of similar structures at refineries throughout the world. The main focus of the investigation is the dynamic response of the stack due to an earthquake motion recorded at a nearby site, named the YPT record. A new 3-D pushover analysis procedure is proposed in this paper and the results will be compared with those of a nonlinear dynamic analysis. Higher mode effects are significant for this type of structure and considered in the proposed 3-D pushover analysis procedure. Results are presented that show the importance of the 3-D interaction effects in the dynamic response of the stack. The results also confirm that the stack could readily fail under the considered earthquake and are consistent with the debris pattern.

KEYWORDS: finite element, chimney, nonlinear 3-D pushover analysis, failure, collapse

1. INTRODUCTION AND OBJECTIVES

This study is focused on a 115 meter high reinforced concrete chimney, which collapsed during the 1999 Kocaeli earthquake. This earthquake caused great damage to inhabited structures and the regional transportation system that has been well documented. The coincident damage to industrial facilities did not produce a high death toll, but the economic repercussions were enormous. Furthermore, many of these facilities were designed and constructed to international standards and provide information that is readily transferable to other developed countries.

The reinforced concrete chimney shown near the center of Figure 1 collapsed during the earthquake. The debris cut many lines, which fueled fires that shut down the refinery for months. The particular distinction of this chimney appears to be an unusually larger rectangular opening, located about 1/3 of the height above the base, which appeared to be the region of collapse initiation. The remnants of the stack are shown in Figure 2.

Figure 1 Heater Stacks before Earthquake

Figure 2 Heater Stacks after Earthquake

The overall objectives of the study are four fold:

(1) To evaluate the original design of the collapsed chimney, known as the Tüpras stack, using current analysis techniques. (2) To evaluate the design of a similar size chimney representative of U. S. practice. (3) To explain why the single stack in question did indeed collapse while several similar structures in the same vicinity survived with minimal damage through the use of advanced seismic evaluation tools. (4) To extend the pushover analysis procedure for chimney structures by taking into account the higher modes and the three dimensional interaction effects.

The input for the study is a single strong motion record recorded at a site near the failed stack, named the YPT (A Petro-Chemical Plant in Körfez, Turkey) record. No other nearby record is available, so this record is adopted as the input motion for the analysis of the Tüpras stack. For the YPT longitudinal spectrum (YPTx) and transverse spectrum (YPTy), along with a modern design code spectrum, UBC 97 (1997 Uniform Building Code) spectrum, several demand curves are plotted in the spectral acceleration vs. spectral displacement domain (ADRS) as shown in Figures 3.

The first two objectives were addressed earlier [Huang, etc. 2004 and 2005] by a response spectrum analysis based on the unsmoothed YPT record as well as the UBC 97 design spectrum.

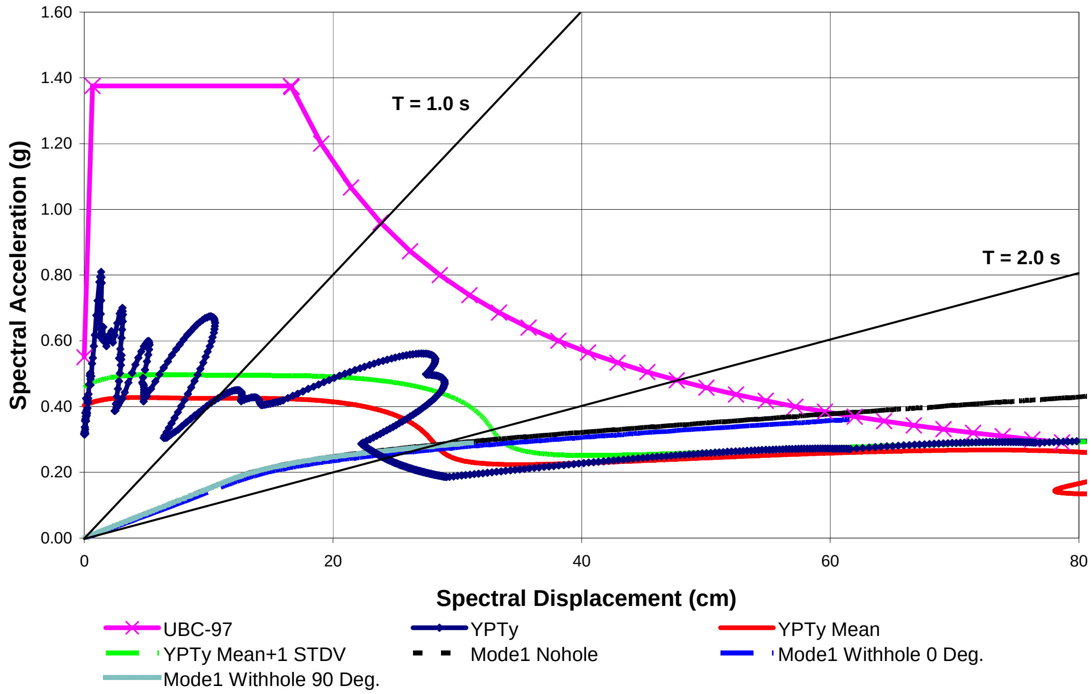

Figure 3 Mode 1 Capacity Curves vs. YPTy Demand Curves

For the third objective, a contemporary nonlinear technique was applied. This method leads to a comparison of demand and capacity as well. In this case, the demand was based on the YPT record and also a smoothed spectrum derived from a statistical earthquake simulation, so as not to overemphasize the local peaks and valleys [Schuëller, etc. 1988].

Pushover analysis is a nonlinear static procedure (NSP) in which a lateral load pattern is applied to the structure and then incrementally increased until the structure reaches the target displacement or collapses. Due to its conceptual simplicity and computational attractiveness as compared to nonlinear dynamic analysis, pushover analysis has been gaining popularity as a tool for seismic design and performance evaluation of structures. However, it has been shown by many researchers that despite its efficiency and applicability, it also exhibits significant limitations when higher modes and 3-D interaction effects play important roles in the dynamic response of the structure. For a chimney structure like the Tüpras stack, this may be the case. How to take those effects into account and develop a simple but improved pushover procedure for seismic design and evaluation of a chimney structure is the fourth objective of the study and the focus of this paper. A new 3-D pushover analysis procedure is introduced in this paper and some comparisons with nonlinear dynamic analysis results are presented.

3. 3-D PUSHOVER ANALYSIS

3.1 A New 3-D Pushover Analysis Procedure

In traditional pushover analysis, only the distribution of forces equivalent to that produced by earthquake action in one direction is applied to the structure to represent the inertia forces experienced during the earthquake. This procedure has provided insightful results for symmetric structures. But for asymmetric structures, pushover analysis considering two directional earthquake input may be more appropriate, since the structure has different dynamic properties in each direction. For the Tüpras stack, with the large opening at the 30 meter level, the stack would have undergone different lateral motions simultaneously and the 3-D interaction effects may not be negligible. There is very little research focusing on improving the pushover analysis by considering three dimensional interaction effects [Ayala, etc. 2002 and Moghadam, etc. 1998], so the need for developing improved pushover analysis procedures considering 3-D interaction effects for asymmetric structures is evident.

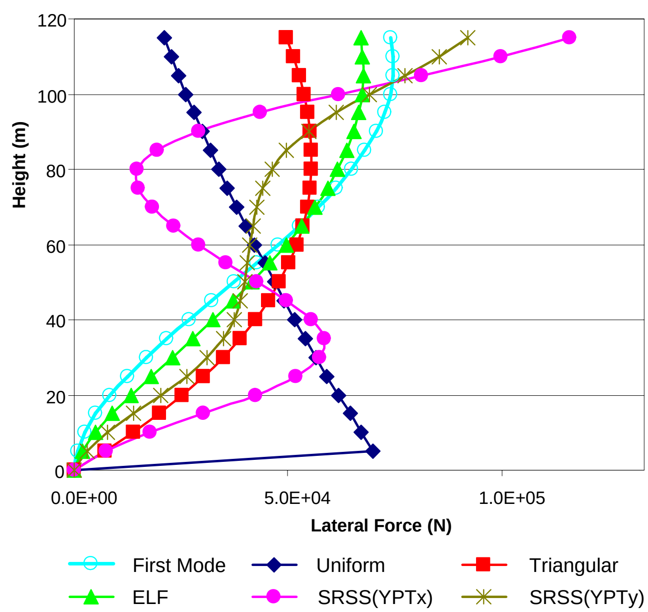

Figure 4 Tüpras Stack Pushover Load Patterns

In this study, a new 3-D pushover analysis method is proposed to extend the traditional 2-D pushover procedure for the analysis of the asymmetric Tüpras stack. The validity of the proposed method will be assessed by comparing the results with those from an "exact" 3-D step-by-step nonlinear dynamic analysis. The basic procedure is as follows:

(1) Carry out a three dimensional modal analysis using a finite element model with the initial geometry and material properties. Obtain the natural frequencies and fundamental modes for each direction.

(2) Now, two types of lateral load patterns may be selected based on the patterns shown in Figure 4. One type is a fundamental mode, usually Mode 1, and the other type may be one of the patterns on Figure 4 other than Mode 1.

(3) For a lateral load pattern other than the fundamental mode patterns, apply the lateral forces to the structure, and perform the pushover analysis for each direction. Plot the pushover curves in the spectral displacement vs. spectral acceleration domain (ADRS). The equivalent SDF period for the lateral load pattern in each direction is then taken as the initial secant for the pushover curve before yielding.

(4) For each direction, given the fundamental frequencies for the fundamental modes and equivalent SDF system frequencies for the other load patterns, locate the corresponding spectral acceleration values from the response spectrum in each direction (In this case, the longitudinal and transverse directions of the YPT spectrum).

(5) Apply two directional lateral forces for each load pattern to the structure, as illustrated in Figure 5,

proportional to the spectral acceleration values obtained from Step 3.

(6) For each load pattern, perform the 3-D pushover analysis using the lateral load forces described in Step 4, and plot the capacity curve for each direction.

(7) Compare the capacity curves with the smoothed mean demand curves of the spectra for each direction to obtain the target displacement of the structure for different load patterns.

(8) Determine the response over the height of the structure using the 3-D pushover analysis results for the different patterns at the respective target displacements.

The validity of the proposed method will be assessed by comparing the results with the three dimensional nonlinear dynamic analysis of the stack.

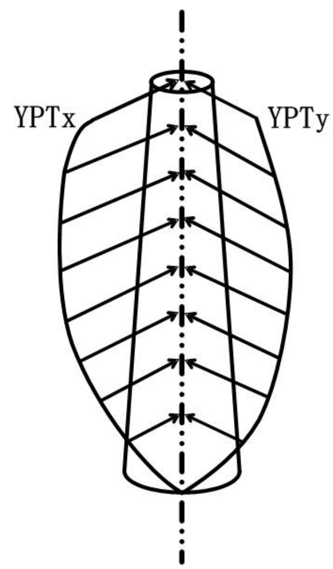

Figure 5 3-D Pushover Load Pattern

3.2 3-D Pushover Analysis Results

First, the 3-D pushover procedure is applied to the model without an opening and compared to 3-D nonlinear dynamic analysis with two directional inputs. The results will not be shown in this paper. Then the procedure is extended to predict the failure of the model with the opening. The failure analysis for the model with the opening is carried out by 3-D nonlinear dynamic analysis as well.

3.2.1 Model with the opening

Since the stack failed in an earthquake having different lateral loading components acting simultaneously, it is appropriate to analyze the structure in multiple directions. The failure displacement and the cracking pattern recorded at the failure point from 3-D nonlinear dynamic analysis will be used to validate the 3-D pushover procedure.

The 3-D pushover procedure was applied to the model with the opening, where the lateral load patterns in the two directions are proportional to the response spectrum values based on the equivalent SDF system. Also, a 3-D nonlinear dynamic analysis was carried out using two directional inputs, a suite of YPT longitudinal records in the direction 0 degrees to the opening, and a suite of YPT transverse records in the direction 90 degrees to the opening, based on the orientation of the opening from the site reference.

The failure displacement at the top and the cracking patterns are compared between the 3-D pushover analysis prediction and the 3-D nonlinear dynamic analysis results.

Failure displacement

Incremental lateral loads in two directions for different loading patterns were applied on the structure until failure. The magnitudes of the top displacement at the point of failure, as predicted by the different pushover patterns, are shown in Table 1. The errors relative to the 3-D nonlinear response history analysis (NL RHA) are listed as well.

Table 1 3-D Failure Displacements for the Model with the Opening

Pattern	YPT Mean	
	Failure Disp. (m)	Error (%)
Mode 1	0.667	27.0
Uniform	0.745	41.8
ELF	0.646	23.1
Triangle	0.645	22.8
SRSS	0.597	13.8
NL RHA	0.525	0

As shown in Table 1, where results taking into account higher mode effects in both directions are summarized, the SRSS distribution provides the best prediction, with less than 14% error.

Cracking pattern

On Figure 6, the cracking patterns for 3-D pushover analysis using different load patterns are plotted at the failure. The failure cracking pattern for the nonlinear dynamic result is shown as NL RHA.

In the failure cracking pattern from nonlinear dynamic analysis, there are more long critical shear cracks around the opening area than there are flexural cracks along the height. This finding confirms the initial prediction by 2-D pushover analysis; the critical shear cracks developed at the opening area caused the stack to fail during that earthquake. The cracking patterns from 3-D pushover analysis show the existence of the critical shear cracks around the top left and bottom right corner of the opening. Considering the limitation of monotonic loading, we would expect a symmetric cracking pattern for the other direction, so the overall cracking patterns around the opening under cyclic loading match well with the nonlinear dynamic analysis results. Even though all lateral patterns give good estimations at the opening level, the SRSS distribution, by taking into account the higher mode contribution, better predicts the cracks developed from the opening level to about the 65 m level.

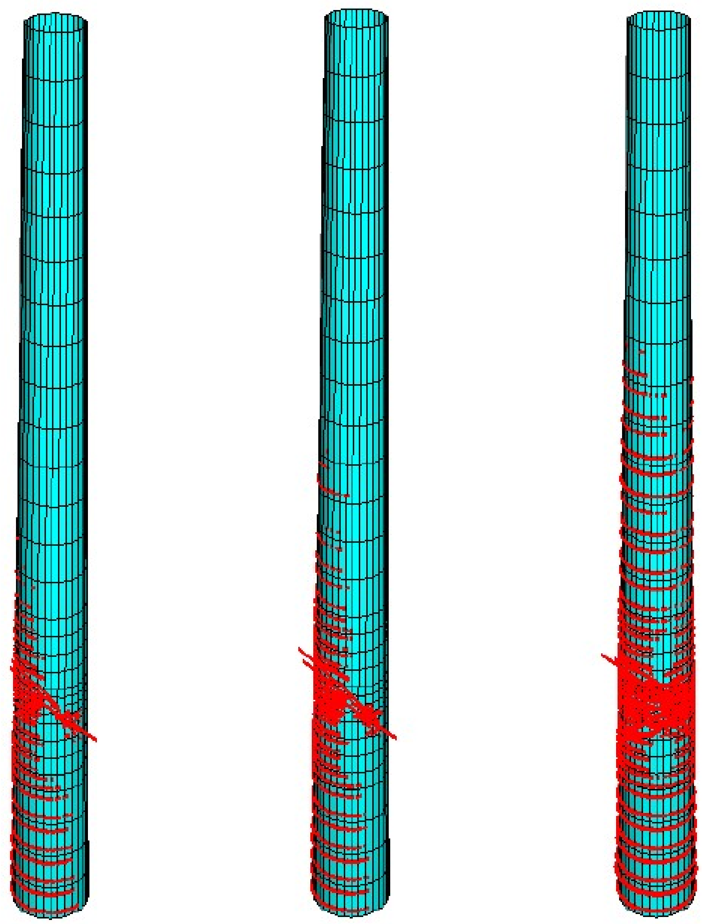

Figure 6 3D Cracking Patterns for Failure of the Model with the Opening

4. CONCLUSIONS

Using a demand-capacity comparison, a nonlinear static pushover analysis was used to investigate the collapsed Tüpras stack. The demand was represented by an acceleration-displacement response spectrum based on the YPT record motion as well as some smoothed adaptations typical of design spectra. The capacities were calculated from pushover curves using a nonlinear reinforced concrete finite element analysis. A new 3-D pushover analysis procedure was proposed and the results were compared with those from a nonlinear dynamic analysis. Based on these pushover analyses, some of the conclusions are summarized as follows:

A new 3-D pushover analysis procedure was proposed and applied to models of chimneys with and without an opening. Various lateral load patterns were considered. For the target displacement of the model without the opening, the error from the Uniform distribution was the largest, while the Mode 1 distribution, ELF distribution, and Triangle distribution provided somewhat better estimates. The SRSS distribution gave a good prediction, with an error around 10% and the error from the MPA procedure was even less than 10%. As to the peak deflections, the MPA procedure and SRSS distribution provided the best estimates, while the Uniform distribution underestimated the total response by up to 30%. The Mode 1 distribution, ELF distribution, and Triangle distribution gave similar estimates. Compared to a 2-D pushover analysis, the new 3-D pushover analysis procedure provides a better estimation for target displacements.

For the 3-D pushover analysis on the model with the opening, the failure displacements predicted using different lateral patterns were in an acceptable range. The SRSS distribution resulted in the lowest error, between 10% and 20%. All of the lateral load patterns successfully captured the shear cracks developed around the opening, along with flexural cracks.

From the failure cracking pattern for the 3-D nonlinear dynamic analysis, there were more long critical shear cracks around the opening area than there were the flexural cracks along the height. This confirmed the initial prediction by 2-D pushover analysis that the critical shear cracking around the opening area, along with the concentrated flexural cracking, was prominent in the failure. The 3-D nonlinear dynamic analysis results confirmed that the Tüpras stack could not survive the YPT earthquake inputs under both directions.

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