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NONLINEAR ANALYSIS OF A COLLAPSED HEATER STACK

Phillip L. GOULD[1], Wei HUANG[2], Raul MARTINEZ[3], Gayle S. JOHNSON[4]

SUMMARY

During the Ismit (Kocaeli) Earthquake of August 17, 1999, a 115 m. high reinforced concrete chimney or heater stack, located at the Tüpras Refinery, collapsed. The falling debris cut 63 pipes, which contributed to interrupted production for more than 14 months. This stack was designed and constructed according to international standards and is representative of similar structures at refineries throughout the world, including those in earthquake-prone regions. It was distinguished from similar stacks at the site by a much larger rectangular opening for the flue duct, circumscribing a horizontal arc of about 50º. The opening was located about 1/3 of the height above the base and appeared to be the region of initiation of the collapse.

The investigation is focused on the dynamic response of the stack due to an earthquake motion recorded at a nearby site. In this paper, the results of a response spectrum analysis of the Tüpras stack and a generic U.S. stack are summarized. Then, a nonlinear static analysis of the collapsed stack is presented using a demand-collapse comparison. The demand is represented by an acceleration-displacement response spectrum based on the recorded motion as well as some smoothed adaptations typical of design spectra, while the capacities are calculated from pushover curves using a nonlinear reinforced concrete finite element analysis.

Results are presented that show the effects of the hole and the orientation of the motion with respect to the hole. Also higher-mode contributions to the pushover pattern are considered. The results confirm that the stack could readily fail under the considered earthquake and are also consistent with the debris pattern.

KEY WORDS: stack; chimney; stress concentration; response spectrum; earthquake analysis

[1] Professor, Washington University, St. Louis, MO, USA. Email: pgoul@seas.wustl.edu
[2] Research Assistant, Washington University, St. Louis, MO, USA. Email: wh3@cec.wustl.edu
[3] Graduate Student, Washington University, St. Louis, MO, USA.
[4] Engineer, Han – Padron Associates, Oakland, CA, USA.

INTRODUCTION

The Kocaeli Earthquake of August 17, 1999 caused great damage to inhabited structures and transportations 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. Perhaps there has never been a recorded earthquake of this magnitude so near to a large heavy industrial area.

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.

Figure 1. Heater stacks before earthquake

Figure 2. Heater stacks after earthquake

Referring to Figure 2, the collapsed heater stack is shown next to a similar structure that survived. The collapsed stack was 115 m high and was distinguished by a large rectangular opening for the flue duct that circumscribed an arc of about 50°. The bottom of the 3.7 m x 4.95 m duct opening was about 30 m from the base. The remnants of the stack are shown more clearly in Figure 3, where it is evident that the failure occurred in the vicinity of the opening.

Figure 3. Remnants of failed stack

The objectives for this study are (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; and (3) to explain why the single stack in question did indeed collapse, while several similar structures in the same vicinity survived with minimal damage.

The input for the study is a single strong motion record recorded at a site nearby the failed stack, named as the YPT record. No other nearby records is available so this record is adopted as the input motion for the analysis of the Tüpras stack. The demand for the first two objectives is provided by a response spectrum analysis based on the unsmoothed YPT record. The comparative capacities of the Tüpras stack and the U.S. stack are based on their respective structural designs, which are somewhat different in approach due to the changes in practice over the years.

For the third objective, a contemporary nonlinear technique is applied. This method leads to a comparison of demand and capacity as well. In this case, the demand is based on the YPT record and also a smoothed record, so as not to overemphasize the local peaks and valleys. The capacities are provided by so-called pushover curves. This approach attempts to determine the differences in the deformation capacities of a chimney with a large opening hole, as opposed to a chimney without such an opening. Also, the direction of the push, either perpendicular to the plane of the opening or 90º to that direction is studied. Additionally, the shape of the vertical lateral load distribution pattern is varied in an attempt to represent higher mode effects.

The study is limited by the absence of any physical data from the failed stack, but is aided by extensive documentation of the design process.

BACKGROUND

There are several recent documents that provide valuable background for this study. Other references are cited in relevant sections of the paper.

The contemporary standard for analyzing existing structures is FEMA 356 [1]. In this document, a hierarchy of four methods is presented, which may be applied to the evaluation of this type of structure: (1) Linear Static Procedure, LSP; (2) Linear Dynamic Procedure, LDP; (3) Nonlinear Static Procedure, NSP; (4) Nonlinear Dynamic Procedure, NDP. The LSP is common for new design and was, in fact, used in the original design of the Tüpras tower. However, it was viewed as inappropriate for this evaluation because the technology for applying the LDP and NSP is available. While a NDP analysis is a worthy objective, it is viewed as too resource-intensive on a continuum model, at least until the results of the other analyses are available. The LDP is applied to objectives (1) and (2) listed in the previous section, while the NSP is used to address objective (3). The results of the LDP study have been presented earlier [2] and are summarized herein, followed by a NSP analysis.

The design of new tall reinforced concrete chimneys is treated by Wilson [3, 4]. From a dynamic behavior standpoint, he characterizes a typical chimney under earthquake excitation as a tuned cantilever that is sensitive to higher mode effects. He stresses the importance of limiting the maximum moments that can be developed by providing for the formation of multiple plastic hinges, rather than a single hinge. This is achieved by properly detailing the sections for the anticipated ductility. A discrete stick cantilever representation of the structure is used to depict the inelastic behavior, thus achieving a NDP solution on this simplified model. It is further claimed that a static pushover analysis, a NSP, cannot predict the "whippy" dynamic response that is dominated by higher mode effects. However, this design philosophy

does not account for the stress concentration and apparent weakness introduced by a very large opening, except for a suggestion to detail such regions so as to provide sufficient overstrength and thus move the critical cross-section elsewhere.

Kilic and Sozen [5] studied the same stack that is the focus of this paper, along with a companion chimney that did not fail. The second stack had two diametrically opposite and smaller openings at different elevations. The structural analysis was apparently confined to the linear range. They consider failure mechanisms corresponding to flexural yielding and shear, but these are dismissed on the basis of comparisons with the like quantities in the surviving stack. Rather, they surmise that the lap splices in the vicinity of the large opening could not maintain continuity under stress reversals in the nonlinear range of response, leading to brittle failure of the stack.

GEOMETRY AND DETAILS

Elevations of the Tüpras chimney and the U.S. chimney are shown in Figure 4, and the steel reinforcing details can be found in Reference 2

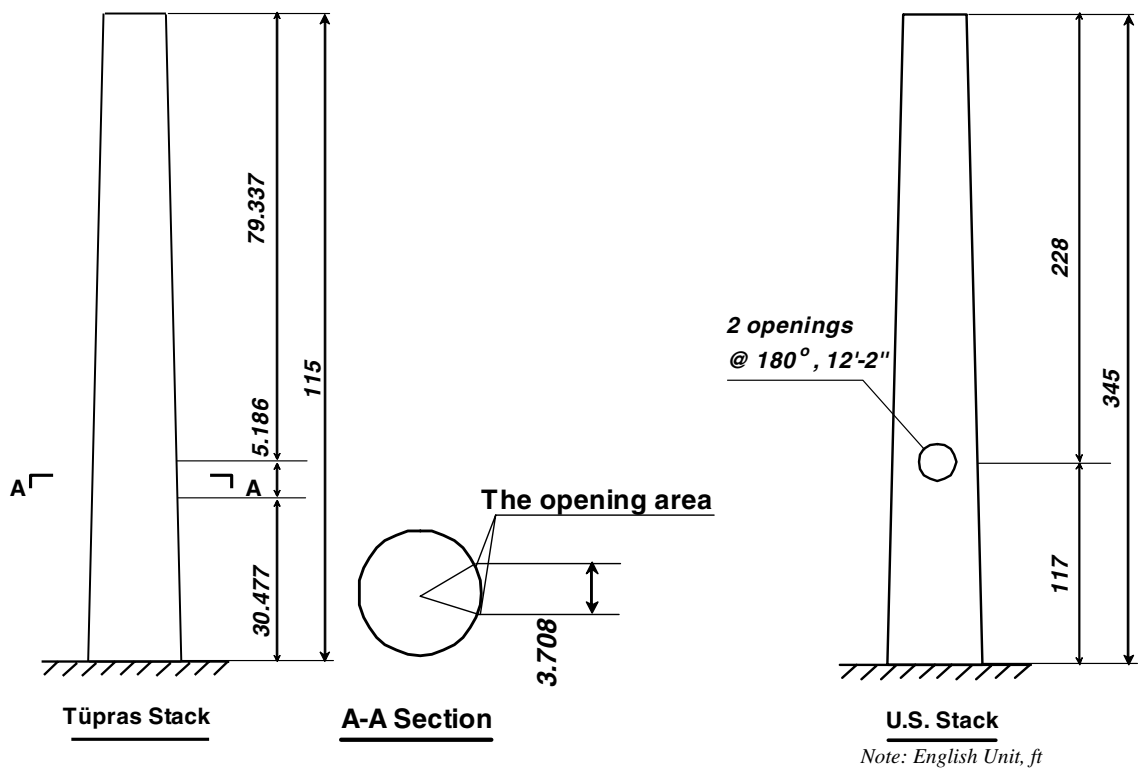


Figure 4. Chimney elevations

The 115 m high Tüpras stack had a bottom outside diameter of 10.3m and a top outside diameter of 6.60 m. The thickness at the bottom was 0.45 m and at the top 0.20 m. It is a single flue reinforced concrete chimney lined with bricks and glass wool. The brick liner started from an annular reinforced concrete slab at level 30.50 m, close to the rectangular flue duct opening, and is supported by corbels at 10 m intervals.

The U.S. stack is dimensioned in English units, which are retained since the reinforcing bars are also specified in these units. It is 345 ft. high, and the bottom outside diameter is 31.54 ft. while the top outside diameter is 23.62 ft. In contrast to the Turkish stack, it has two diametrically opposite round openings.

LINEAR DYNAMIC ANALYSIS

Time history and response spectra

In Figure 5, the time history of the motion recorded for three directions, and the corresponding response spectra for the transverse direction are shown. The spectrum for the longitudinal direction is similar.

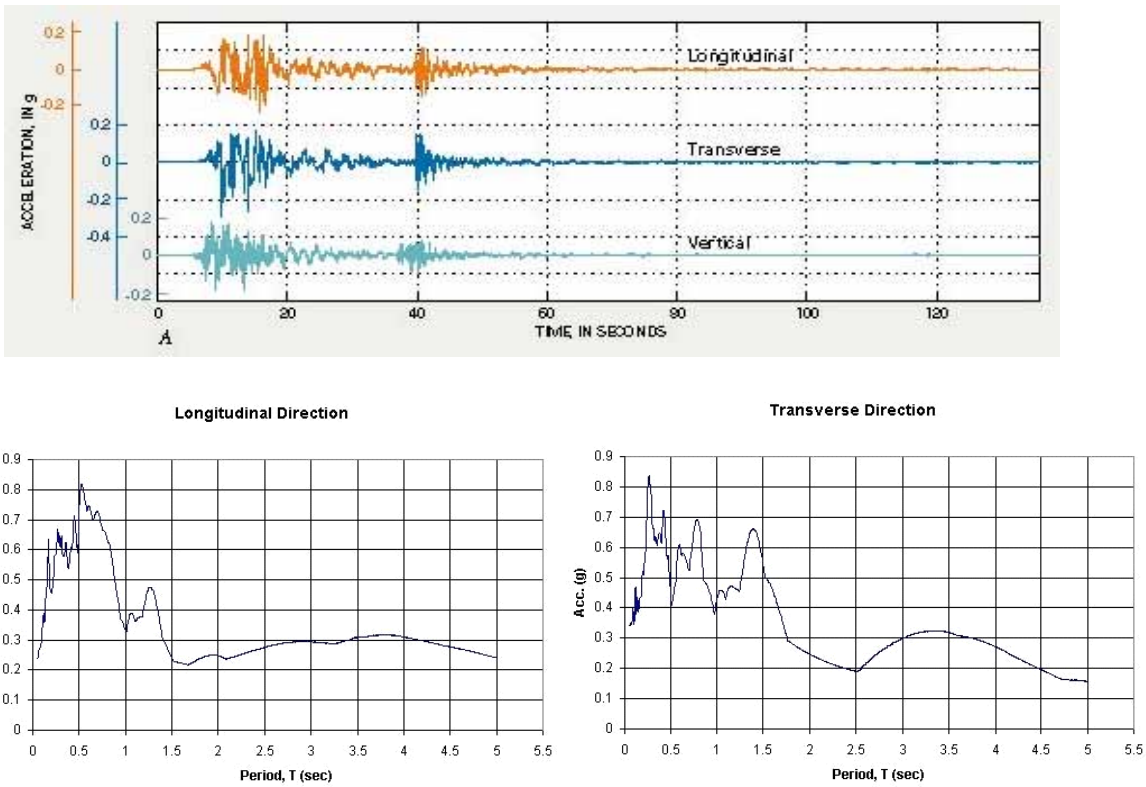


Figure 5. YPT time history and response spectra

Demand-capacity comparison

A comparison of the demand from the YPT response spectrum shown in Figure 5 and the capacity of each stack based on a linear dynamic analysis was presented in Reference 2. It was concluded that the Tüpras stack was subjected to an earthquake somewhat in excess of the design event. Since other similar stacks in the immediate vicinity survived with minimal damage, the large opening was the likely triggering point for the collapse. It is anticipated that the U.S. stack, having lighter reinforcement and large openings, would have suffered the same fate.

NONLINEAR STATIC ANALYSIS

General

The nonlinear static procedure in ATC-40 [6] is based on the capacity spectrum method, which has become a standard procedure for the evaluation of existing structures due to its utility in predicting inelastic dynamic performance. Application of this technique requires that both the capacity of the structure derived from a pushover analysis and the demand given by a selected ground motion spectrum be compared in the spectral acceleration vs. spectral displacement (ADRS) domain. In this paper, the NSP is performed only on the Tüpras stack in order to obtain the several comparative results described in the introductory section. These results are directed toward a plausible quantitative explanation of the unique failure of the stack.

While the lateral load patterns should be selected to approximately represent and bound the likely distribution of the inertia forces during the earthquake, none of the current invariant force distributions can fully account for the higher mode effects and the possible redistribution of inertia forces due to structural yielding. Different suggestions have been made to overcome these limitations, including the adaptive lateral force distributions [7, 8] and the recently developed Modal Pushover Analysis (MPA) procedure [9]. In the MPA procedure, the seismic response of the building due to each mode is determined by pushing the structure to its modal target displacement using an invariant modal lateral force distribution. The overall peak response of the structure is then estimated by combining the peak response for each mode using an appropriate modal combination rule, e.g. the SRSS rule.

The mode-by-mode approach of the MPA procedure is appealing and may eventually be applicable to the present study. However, the determination of the modal target displacement is beyond the current scope, so that a combined lateral load pattern, as recommended in FEMA 356 [1], is used to fulfill the third objective stated in the introduction section. Two load patterns, the first mode distribution and the SRSS distribution are selected. For the purpose of the current study, which is focused on the localized stress conditions in the vicinity of the large opening at level 30, the SRSS distribution based on the first 3 modes captures the essential demands. Combining modal responses from a response spectrum analysis, the SRSS distribution is considered appropriate to account for higher mode effects in the pushover procedure.

Demand curves

From the YPT response spectrum shown in Figure 5, an equivalent Acceleration-Displacement Response Spectrum or Demand Spectrum may be constructed using the procedure of ATC-40 [9]. Since the basic procedure described in ATC-40 emphasizes a smoothed spectrum, such a curve is constructed from the mean ordinates in the Acceleration-Period space and mapped into the Acceleration-Displacement space. Also, a smoothed spectrum for the mean plus one standard deviation is plotted in the same way. The latter spectrum is recommended to account for near–fault effects [10]. Finally, a UBC-97 spectrum is constructed as an example of a modern design spectrum incorporating near-fault effects.

All of these demand curves are shown in Figure 6.

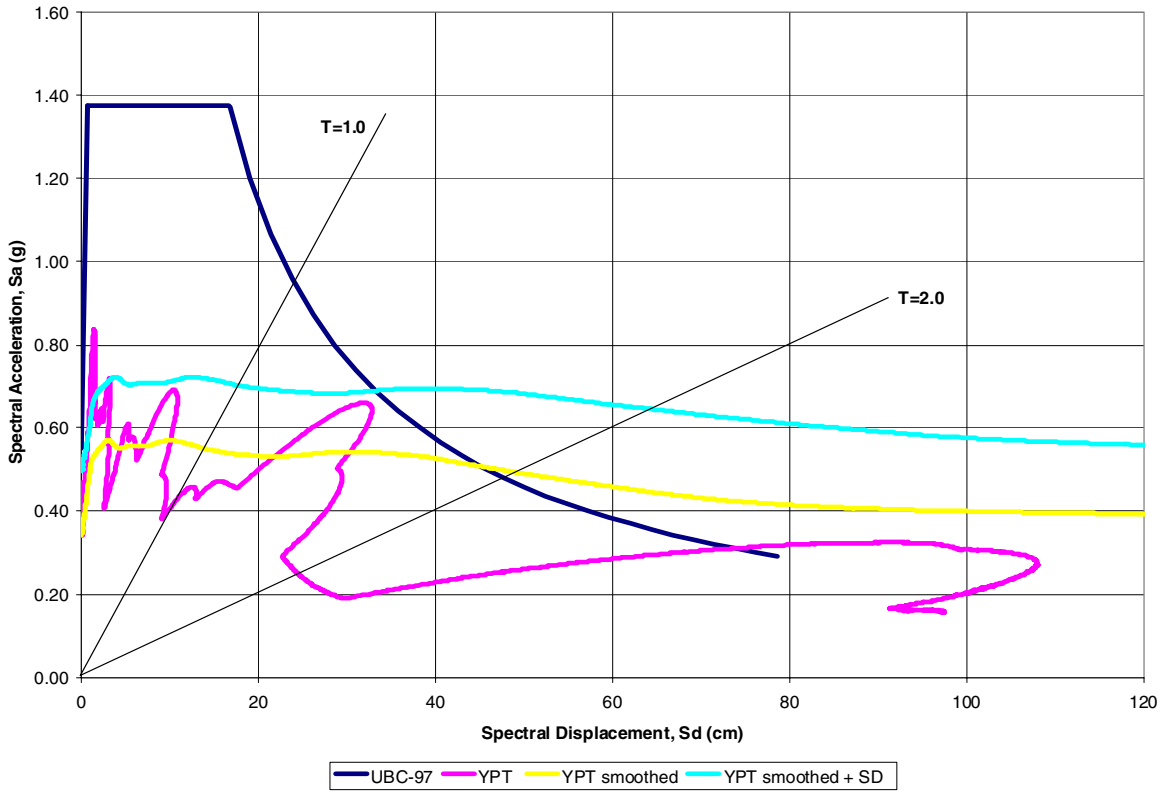


Figure 6. Demand curves

Capacity curves

The capacity of the structure is evaluated by first performing a pushover analysis using the nonlinear finite element capabilities of ABAQUS. The FE mesh was perfected during the LDP analysis and is retained for this NSP study.

The modeling of reinforced concrete in ABAQUS incorporates many standard advanced features to represent the concrete material as it progresses through various stages of cracking, and the steel reinforcement as it participates in the composite resistance of the structure. All of the features are described in detail in the User's and the Theoretical Manuals for the program [11] and are only briefly noted here. The concrete and rebar elements are defined independently, with the interface provided through the tension stiffening parameters. Cracking is assumed to occur when the stress reaches a failure surface, called the crack detection surface. These surfaces account for multi-axial states of stress and are calibrated to experimental data, either user–supplied or default. The cracks are smeared and irrecoverable, and the material response after cracking is described by an oriented damaged elasticity model. As noted before, tension stiffening, with a fracture energy cracking criterion, and cracked shear retention are included. Since tension stiffening is used to represent effects associated with the rebar/concrete interface such as bond slip and dowel action, the tension stiffening parameter is chosen following the recommendation in the ABAQUS manual [11].

In ABAQUS, structural failures are associated with non-convergence of the numerical analysis. When there are too many cracks concentrated in local areas, the significant stiffness loss for cracked elements terminates the analysis, which is considered an appropriate failure condition for the structure. Since direct cracking pattern plotting was not available in the version of ABAQUS used, an independent method of crack plotting was developed.

In order to properly compare the demand and capacity, the capacity curve is converted to a capacity spectrum using the procedure of ATC-40 insofar as it is applicable to the present cases.

The pushover capacity curves of the first and SRSS modes of the stack are plotted along with the demand spectra in Figures 7 and 8. In addition to the aforementioned demand curves, three pushover analysis curves are now plotted: the model without the opening; the model with the opening pushed parallel (0 deg.) to the opening; and then pushed perpendicular (90 deg.) to the opening. Figure 7 is based on a pushover profile following the shape of the first mode while Figure 8 was constructed from the SRSS profile.

First mode demand-capacity comparison

Figure 7 shows that the model without the opening performed very well with ample ductility, which is consistent with the study of Wilson [4]. The capacity of the model with the opening (90 deg.) is the lowest of the three pushover cases while the failure point for the model with the opening (0 deg.) is between the other two. It is clear from the figure that neither the 90 deg model nor the 0 deg. model capacities meet the demand of the smoothed YPT spectrum. The capacity of the 90 deg. model is especially indicative of the possible failure mode of the structure during the earthquake in that it does not intersect the smoothed demand curve.

In order to better track the cracking development during the analysis, three phases of cracking patterns are plotted for each pushover curve, the initial crack phase, the middle crack phase, and the failure phase. The locations of these phases on the capacity curves are shown in Figure 7. For the model without an opening, as shown in Fig. 9, the flexural cracks started at the base level and extended upwards to about two-thirds of the stack height. The failure of this structure is clearly due to flexure. For the model with an opening, pushed at 0 deg. and shown in Fig. 10, the failure mode initiated with the cracks around the opening and developed downward to the base level. After the opening apparently attracted most of the cracks, the failure occurred when the cracking propagated to the middle height of the stack. For the model with an opening pushed at 90 deg. and shown in Figure 11, the first cracks occurred at the base level and the area around the opening. Then more cracks developed around the opening and at about one-third of the height from the base. The formation of many critical shear cracks around the opening, as shown in details in Fig.12, leads to the failure. Compared with the other two pushover results shown in Figure 9 and 10, the flexural cracks along the stack height shown in Figure 11 are much less developed before the collapse occurred.

SRSS mode demand-capacity comparison

A similar analysis was performed for the SRSS pushover profile. As shown in Figure 8, the sequence of three capacity curves is very similar to those for the first mode profile. It is observed that all of the capacities for the structure under the SRSS load pattern are comparatively less than the first mode pattern results. Furthermore, the two cases for the stack with the opening do not even meet the demand of the **unsmoothed** spectrum. The cracking pattern for this case is very similar to the previous plots shown on Figures 9 - 12. Further results are available on the project website: **http://www.cive.wustl.edu/~whuang/.**

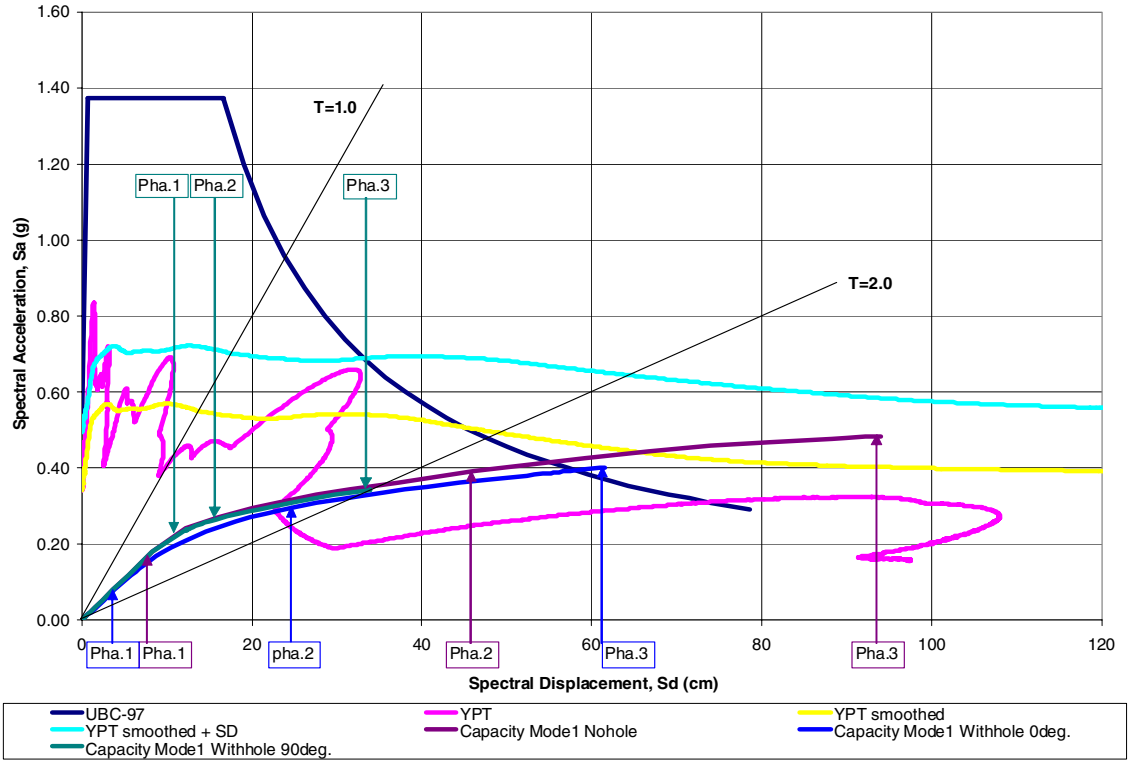


Figure 7. Demand curves vs. first mode capacity curves

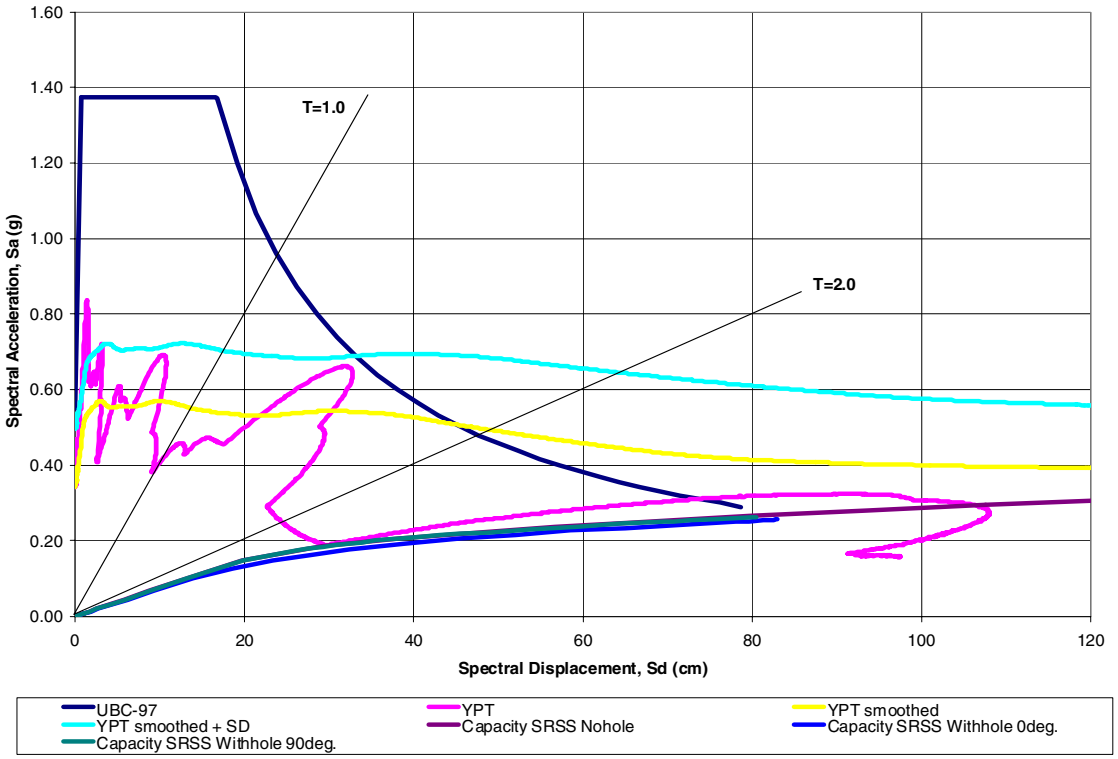
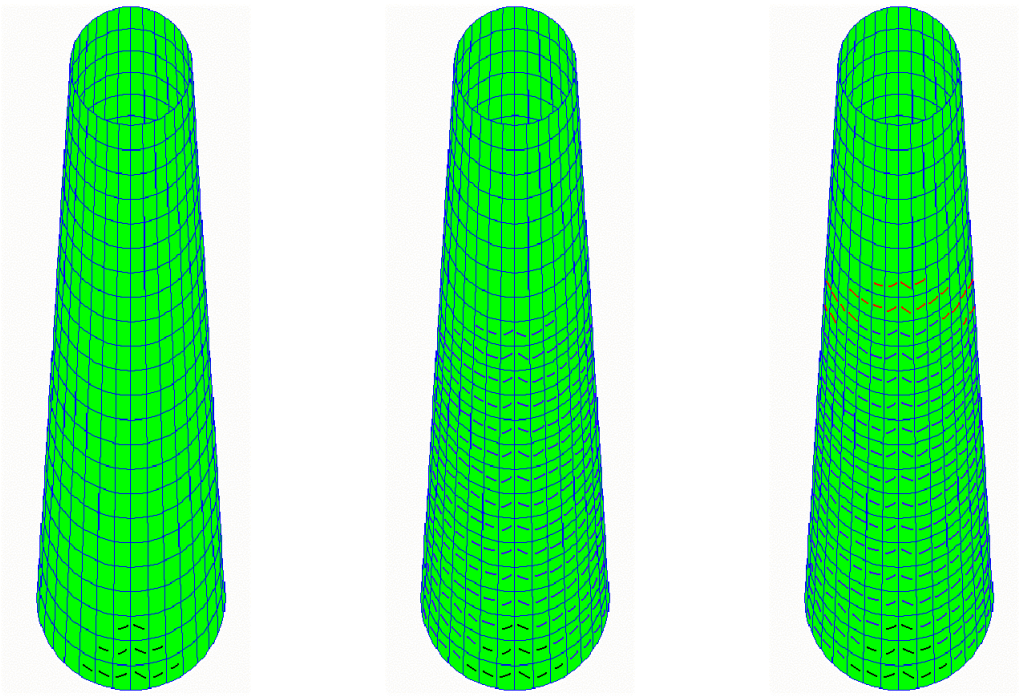
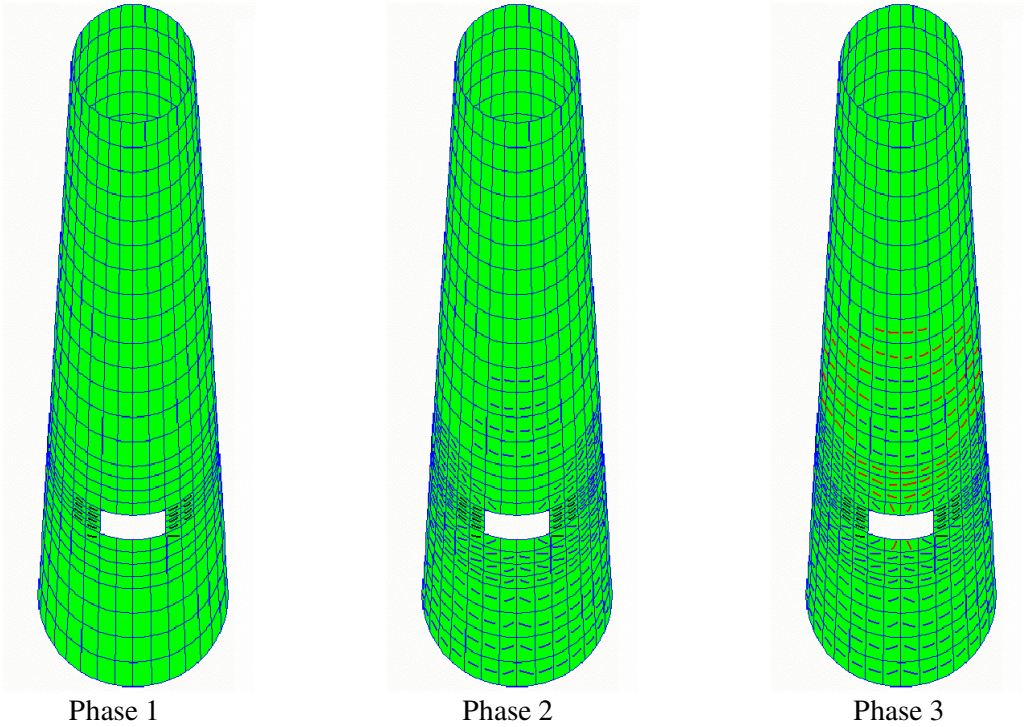


Figure 8. Demand curves vs. SRSS mode capacity curves



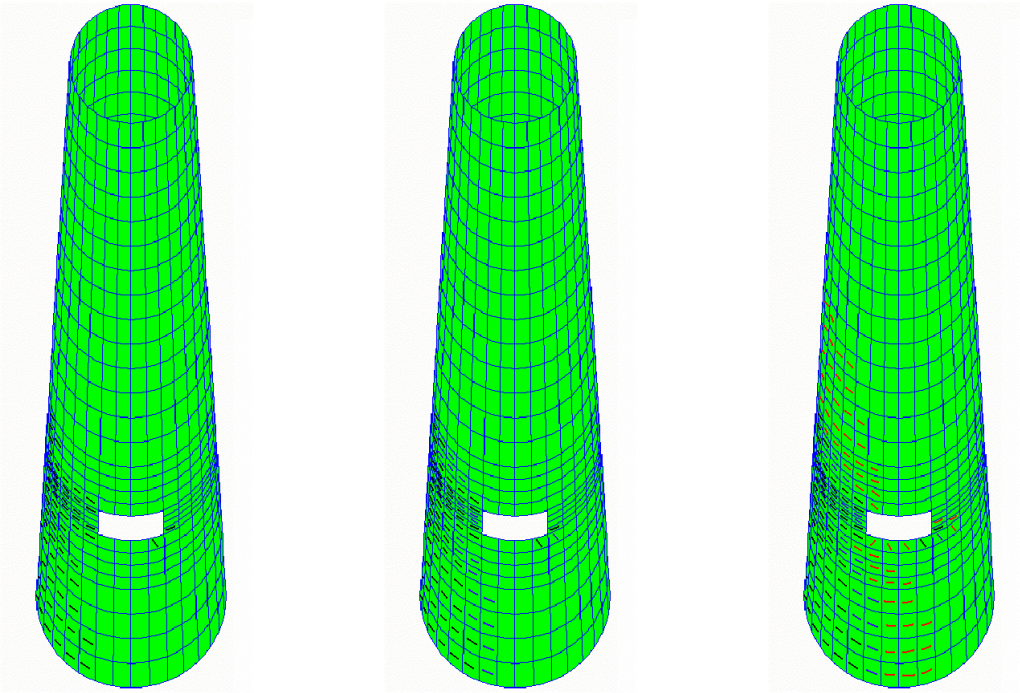
Push direction ⇑

Figure 9. Cracking pattern for the model without opening



Push direction ⇑

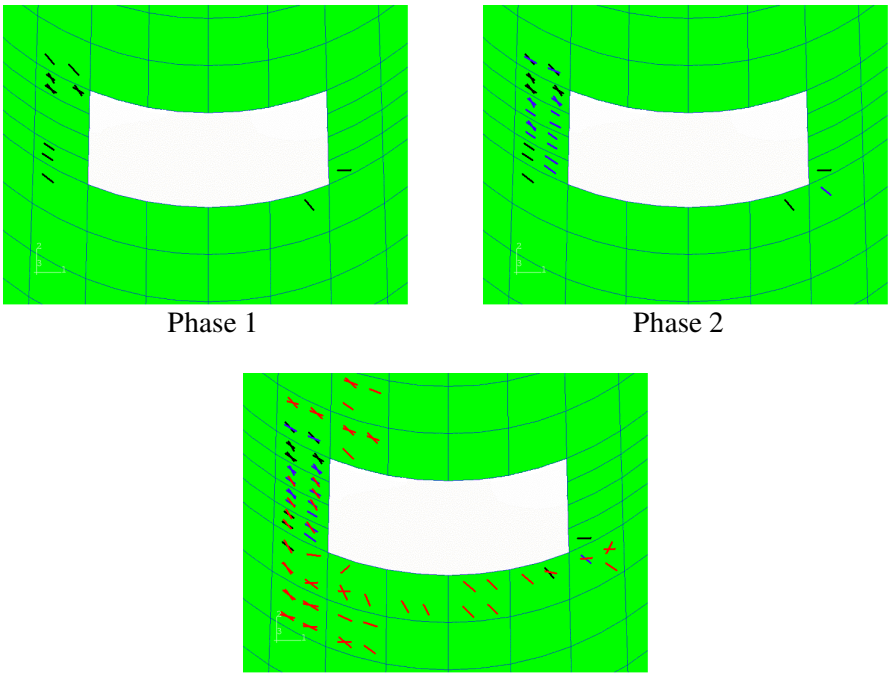
Figure 10. Cracking pattern for the model with opening (0 deg.)



Phase 1 Phase 2 Phase 3

Push direction ⇒

Figure 11. Cracking pattern for the model with opening (90deg.)



Phase 1 Phase 2

Phase 3

Push direction ⇒

Figure 12. Cracking pattern details around the opening (90 deg.)

Comparison to Observed Damage

A sketch of the debris from the collapsed tower was made available to the authors. This is shown in Figure 13 and seems to confirm that the loading at 90 deg to the opening presents the weakest capacity for static resistance.

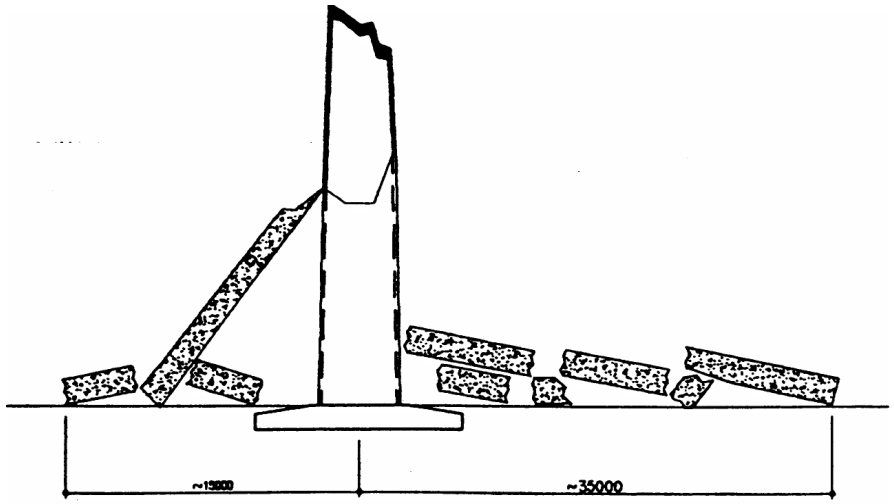


Figure 13. Fragments of collapsed tower looking straight on at the opening

CONCLUSIONS

A reinforced concrete chimney that collapsed during the 1999 Ismit earthquake was studied, first using a linear dynamic response spectrum method and then by a nonlinear static capacity spectrum analysis. This stack was the only one of several in the immediate vicinity that collapsed, and was distinguished by an abnormally large rectangular opening located at about one-third of its height up from the base. The response spectrum analysis revealed that the stack was subjected to section forces considerably in excess of the design capacity, which did not explicitly account for the effect of the opening. The nonlinear capacity spectrum analysis produced a variety of demand-capacity comparisons, which revealed that the strength of the stack, including the effect of the opening, at best barely met the demand and in some cases fell short. The results provide a plausible explanation for the failure in the direction 90 degrees from the opening, which is also consistent with the observed debris field. Of course, a full nonlinear dynamic analysis would be necessary to more completely simulate the failure. This analysis is underway.

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