POINT BEACH

January 14, 2010

NRC 2010-0010
10 CFR 50.90

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555

Point Beach Nuclear Plant, Units 1 and 2
Dockets 50-266 and 50-301
Renewed License Nos. DPR-24 and DPR-27

Transmittal of Information to Support
License Amendment Request 241, Alternative Source Term
Seismic Evaluation Guidelines for HVAC Duct and Damper Systems

Reference:
(1) FPL Energy Point Beach, LLC letter to NRC, dated December 8, 2008, Submittal of License Amendment Request 241, Alternative Source Term (ML083450683)
(2) NextEra Energy Point Beach, LLC, Letter to NRC, dated November 20, 2009, Transmittal of Information to Support License Amendment Request 241, PBNP VNPAB and CREFS Seismic Evaluation (ML093310308)

NextEra Energy Point Beach, LLC (NextEra) submitted License Amendment Request 241 (Reference 1), Alternative Source Term (AST), to the NRC pursuant to 10 CFR 50.90.

The NRC requested additional information regarding the seismic adequacy of the control room emergency filtration system (CREFS) and primary auxiliary building ventilation system (VNPAB) credited in the AST analyses. Via Reference (2), NextEra submitted the results of the VNPAB and CREFS seismic evaluation to address this request.

The NRC has requested that NextEra provide a copy of the Electric Power Research Institute (EPRI) Technical Report 1014608 referenced in the seismic evaluation in order for the Staff to provide site-specific approval of the use of the report for the Point Beach Nuclear Plant.

Enclosure 1 provides a copy of "EPRI Technical Report 1014608, Seismic Evaluation Guidelines for HVAC Duct and Damper Systems, Revision to 1007896," dated December 2006.

This letter contains no new Regulatory Commitments and no revisions to existing Regulatory Commitments.

The information contained in this letter does not alter the no significant hazards consideration contained in Reference (1) and continues to satisfy the criteria of 10 CFR 51.22 for categorical exclusion from the requirements of an environmental assessment.

In accordance with 10 CFR 50.91, a copy of this letter is being provided to the designated Wisconsin Official.

I declare under penalty of perjury that the foregoing is true and correct.
Executed on January 14, 2010

Very truly yours,

NextEra Energy Point Beach, LLC

FOR

Larry Meyer
Site Vice President

Enclosure

cc: Administrator, Region III, USNRC
Project Manager, Point Beach Nuclear Plant, USNRC
Resident Inspector, Point Beach Nuclear Plant, USNRC
PSCW

ENCLOSURE 1

NEXTERA ENERGY POINT BEACH, LLC
POINT BEACH NUCLEAR PLANT, UNITS 1 AND 2

LICENSE AMENDMENT REQUEST 241
ALTERNATIVE SOURCE TERM

EPRI TECHNICAL REPORT 1014608, SEISMIC EVALUATION GUIDELINES FOR HVAC DUCT AND DAMPER SYSTEMS, REVISION TO 1007896
FINAL REPORT, DECEMBER 2006

174 pages follow

ELECTRIC POWER
RESEARCH INSTITUTE

Seismic Evaluation Guidelines for HVAC Duct and Damper Systems

Revision to 1007896

WARNING:
Please read the Export Control Agreement on the back cover.

Technical Report

Seismic Evaluation Guidelines for HVAC Duct and Damper Systems

Revision to 1007896

1014608

Final Report, December 2006

EPRI Project Manager
R. Kassawara

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CITATIONS

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This report describes research sponsored by the Electric Power Research Institute (EPRI).

The report is a corporate document that should be cited in the literature in the following manner:

Seismic Evaluation Guidelines for HVAC Duct and Damper Systems: Revision to 1007896.
EPRI, Palo Alto, CA: 2006. 1014608.

REPORT SUMMARY

This report provides guidelines that can be used to perform an experience based seismic capability verification of HVAC duct and damper systems in nuclear power plants. The report summarizes seismic experience data from strong-motion earthquakes for these systems and identifies the characteristics of systems that could lead to failure or unacceptable behavior in an earthquake. The seismic experience data show that HVAC duct and damper systems exhibit extremely good performance under strong-motion seismic loading, with the pressure boundary being retained in all but a handful of cases. This revision of the original report includes a successful trial application of the methodology to a non-seismically designed HVAC system.

Background
The Seismic Qualification Utility Group (SQUG) provides guidelines for seismic capability verification of nuclear plant electrical and mechanical equipment; relays, tanks and heat exchangers; and electrical raceway systems using seismic experience and test data. As part of this effort, the performance of HVAC duct and damper systems in 100 power and industrial facilities in more than 20 strong-motion earthquakes has been compiled into a seismic experience database. This database has been used to establish guidelines to seismically verify as-installed HVAC duct and damper systems and screen out potential failure modes and undesirable conditions that could lead to seismic damage or failure.

Objectives
To provide guidelines that can be applied to as-installed HVAC duct and damper systems to demonstrate seismic ruggedness

Approach
The research team assembled data on the seismic performance of HVAC duct and damper systems from over 20 strong-motion earthquakes since 1971. The team studied these data to determine failure modes, capacities, and success parameters. They used the recorded experience data to develop guidelines for evaluation of ductwork and dampers. Following the original issue of this report, Southern Nuclear conducted a trial application of the methodology to verify the seismic adequacy of a non-seismically designed HVAC system at Hatch Unit 1. The trial application included a peer review by Dr. Robert P. Kennedy. The peer review comments are included in this report as Appendix G.

Results
The guidelines in this report can be used to demonstrate the seismic capability of HVAC duct and damper systems. The recommended seismic adequacy review procedure includes documentation review, in-plant screening walkdowns, analytical review of selected duct runs and supports, and identification and resolution of outliers that do not meet the screening or analysis

criteria. Documentation is reviewed to determine input parameters such as system identification, function, system boundaries, operating conditions, materials, and seismic input. Field walkdowns, which should be performed by qualified personnel who meet SQUG experience and training requirements for Seismic Capability Engineers, are used to screen the HVAC duct and damper systems for known seismic vulnerabilities and undesirable conditions that could lead to damage or failure in a seismic event. The walkdown team reviews the as-installed HVAC duct and damper system against a checklist of conditions to assess acceptability. As part of the field walkdowns, the review team selects and details representative, worst-case samples of duct runs and duct supports for analytical review. The guidelines include criteria for this analytical review. Appendix A of this report summarizes the seismic experience database for HVAC duct systems. Appendix B summarizes the seismic experience database for dampers.

The revised report now incorporates lessons learned from the trial application of the methodology at Hatch Unit 1 and the recommendations of the peer reviewer. The trial application was successful and proved the methodology to be a practical, effective and cost-effective means to verify the seismic adequacy of HVAC duct and damper systems. There was a significant cost savings to the plant in not having to design and install seismic bracing on the ductwork.

EPRI Perspective

The use of seismic experience data from actual strong-motion earthquakes has proven to be a reliable and cost effective method for seismic capability verification. Accordingly, SQUG has developed the Generic Implementation Procedure, which structures the method and applies it to some twenty different classes of nuclear plant equipment, relays, tanks and heat exchangers, and electrical raceways. As part of SQUG's ongoing effort to expand the method to new classes of equipment, this report extends the method to HVAC duct and damper systems and provides guidelines to demonstrate seismic adequacy of existing HVAC duct and damper systems. The appendices to this report provide a summary of seismic experience for HVAC duct and damper systems in a database that has been assembled from power and industrial facilities located in the strong-motion areas of over 20 earthquakes. This database provides valuable information on the performance of HVAC duct and damper systems in earthquakes, and will enhance the industry's overall database of seismic performance of equipment and systems.

Keywords

Damper
Duct
Earthquakes
HVAC
Seismic Effects
Seismic Experience Data
Seismic Verification Guidelines

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of Mr. Donald P. Moore, Southern Company Services, who provided valuable insights from application of this methodology at Plant Hatch; Dr. Robert P. Kennedy, RPK Structural Mechanics Consulting, who performed peer reviews of Revision 0 of this report and the Plant Hatch implementation, and provided valuable comments; and Mr. Richard Starck, MPR Associates, who provided review comments during preparation of Revision 1 of this report.

The authors also wish to acknowledge the contributions of Mr. John Dizon, Facility Risk Consultants, and Mr. Farzin Beigi, ABS Consulting, for their contributions to the original issue of this report.

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1 INTRODUCTION

1.1 Background

This report provides guidelines for seismic adequacy review of HVAC duct and damper systems. The screening guidelines are primarily based on seismic experience data that show that most types of HVAC duct and damper systems exhibit extremely good performance under strong-motion seismic loading, with the pressure boundary being retained in all but a handful of cases. The guidelines provide a method to screen and identify features seismic vulnerabilities and weaknesses.

The guidelines rely on the evaluation of seismic failure mechanisms for duct and damper systems from seismic experience data presented in Appendices A and B of this report. The data show that the damage to duct systems are generally limited to direct seismic damage of the duct or supports, and local damage due to seismic interaction with adjacent commodities. Seismic damage to HVAC duct systems documented in the seismic experience database can be attributed to the following categories:

- *Broken and Fallen Cantilevered Sections.* Cantilevered sections of duct and duct diffusers have broken due to high inertia loading at weak joints, and due to inadequate flexibility of short duct segments to accommodate header movement.
- *Opened and Sheared Seams.* Light gage circular duct constructed with riveted lap joints have opened up and sheared in past strong-motion earthquakes. This damage has occurred at locations subject to high bending strain in very flexible duct systems.
- *Duct Fallen off Support.* The database includes one example where the end of a cantilevered duct section jumped off of its end hanger support and was damaged. The duct was not tied to the support, and was subject to high levels of seismic motion.
- *Equipment on Vibration Isolators.* HVAC duct has been damaged by excessive movement of in-line equipment components supported on vibration isolators.

The seismic experience database indicates that dampers possess characteristics that generally preclude damage in earthquakes. The experience database contains no instances of damage or significant seismic effects to dampers or their actuators.

Following the original issue of this report, Southern Nuclear conducted a trial application of the methodology to verify the seismic adequacy of a non-seismically designed HVAC system at Hatch Unit 1. The trial application included a peer review by Dr. Robert P. Kennedy. The peer review comments are included herein as Appendix G. Revision 1 of this report incorporates lessons learned from the trial application and the recommendations of the peer reviewer.

The trial application was successful and proved the methodology to be a practical, effective and cost-effective means to verify the seismic adequacy of HVAC duct and damper systems. There was a significant cost savings to the plant in not having to design and install seismic bracing on the ductwork.

1.2 Overview of Guidelines

The guidelines for seismic adequacy review of HVAC duct and damper systems include the following sections:

- Applicability and Qualifications (Section 2)
- Walkdown Screening Guidelines (Section 3)
- Analytical Review Criteria (Section 4)

Section 2 provides general requirements the HVAC duct and damper system must meet to be able to use these guidelines for seismic verification. Section 2 also includes qualification requirements for individuals who perform the seismic adequacy review.

Section 3 presents guidelines for conducting in-plant seismic adequacy review of the HVAC duct and damper systems including supports. These walkdown guidelines are used to screen out potential failure modes indicated by seismic experience data, and to ensure database representation of the duct and damper system. As part of the walkdown, representative worst-case examples of duct supports are identified by the walkdown team and detailed for analytical review. In addition, representative worst-case examples of duct runs are identified by the walkdown team and detailed for analytical review for duct systems that require pressure boundary integrity to be maintained.

Section 4 includes criteria for performing analytical review of representative samples of duct systems and supports selected by the walkdown team. When these representative samples do not pass the analytical review, further evaluations should be conducted and the sample expanded as appropriate.

The results of the walkdown are documented in walkdown notes and forms included in Section 5.

Section 6 describes outliers and how they may be resolved.

References are included in Section 7.

A summary of the seismic experience database for HVAC duct systems is included in Appendix A. The seismic experience database for dampers is included in Appendix B. These appendices provide details on the performance of HVAC duct and damper systems at selected industrial and power plant facilities in actual strong-motion earthquakes. Appendix C contains an example calculation of allowable span tables from the trial application. Appendix G contains the peer review comments from the trial application.

2
APPLICABILITY AND QUALIFICATIONS

2.1 Applicability

These guidelines apply to existing heating, ventilation and air-conditioning (HVAC) ducts, dampers and supports. Appurtenances such as registers, access doors, turning vanes, filters, louvers, air diffusers and similar components normally attached to HVAC ducts are also included. These guidelines apply to duct fabricated of hot-rolled and cold-rolled carbon steel, galvanized sheet steel, stainless steel and aluminum within the following maximum operating temperature limitations:

Table 2-1
Temperature Limitations for Duct Materials

Material	Maximum Temperature
Hot-Rolled Carbon Steel	400°F
Cold-Rolled Carbon Steel	400°F
Galvanized Sheet Steel	400°F
Stainless Steel	400°F
Aluminum	300°F

The guidelines are applicable to any HVAC duct and damper system at any elevation in a plant where the nuclear plant free-field ground motion 5% damped seismic design spectrum does not exceed the Seismic Motion Bounding Spectrum of Reference [1] and the horizontal zero period acceleration (ZPA_h) of the in-structure response spectra at the HVAC support anchorage does not exceed 2.0g. The Bounding Spectrum is shown in Figure 2-1. The 2.0g ZPA_h restriction is from Reference [16].

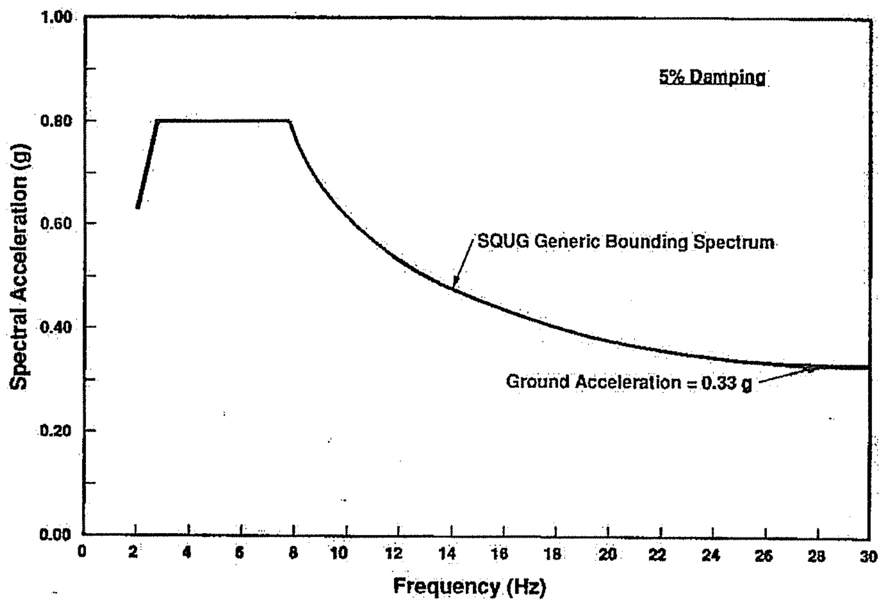


Figure 2-1
Seismic Motion Bounding Spectrum

2.2 Qualifications

These guidelines are intended to be applied by qualified engineers who meet the training and experience requirements defined in this section.

The Seismic Review Team (SRT) should consist of at least two engineers who meet the requirements for Seismic Capability Engineers (SCEs) as defined in Section 2 of Reference [1]. These individuals are required to be degreed engineers, or equivalent, who have completed a SQUG developed training course on seismic adequacy verification of nuclear power plant equipment. They are required to have at least five years experience in earthquake engineering applicable to nuclear power plants and in structural or mechanical engineering. At least one engineer on each Seismic Review Team should be a licensed professional engineer.

In addition, qualified users of these guidelines must be familiar with the following topics:

- Content and intent of the guidelines
- HVAC duct and support design requirements of the Sheet Metal and Air Conditioning Contractor's National Association, Inc., (SMACNA), including References [4] through [7]
- Seismic experience data for HVAC duct and damper systems

2.3 Peer Review

The earthquake experience based seismic evaluation approach presented herein relies heavily on the judgment and experience of the SRT. This judgment and experience is used in lieu of extensive analysis. The SQUG GIP, Reference [1], and EPRI SMA, Reference [14], also utilize an experience based approach. The USNRC required the implementation of these methodologies include an independent peer review of the judgments and conclusions made by the SRT as well as a sampling review of the limited analytical evaluations. As part of the application of the guidelines of this report, it is therefore recommended that use of the methodology include an independent peer review by a knowledgeable individual who is not a member of the SRT.

3 WALKDOWN SCREENING GUIDELINES

3.1 Overview of Walkdown Guidelines

This section presents requirements for performing the in-plant screening review of HVAC duct and damper systems for structural integrity, support review, seismic interaction, and pressure boundary integrity. Requirements are also provided for the selection of bounding/sample configurations for subsequent analytical evaluation. Analytical evaluation criteria are covered in Section 4. Screening and evaluation work sheets (SEWS) for recording information from the in-plant screening review are provided in Section 5.

The HVAC duct system seismic evaluation consists of two phases, (1) an in-plant screening review of field conditions to evaluate as-installed configurations for seismic deficiencies and (2) the analytical evaluation of selected duct and/or support configurations. The specific requirements for the evaluation are dependent upon the functional pressure boundary integrity requirements desired.

The in-plant screening review of HVAC duct systems encompasses the following:

- Review duct system structural features that may lead to poor performance as illustrated by the seismic experience and test data (Section 3.2).
- Review support system for undesirable conditions that may lead to poor performance (Section 3.3).
- Review potential seismic interaction hazards (Section 3.4).
- Review duct system features to provide a high confidence level that pressure boundary integrity is assured. These requirements are based on seismic experience and test data (Section 3.5).
- Identify bounding configurations/samples for analytical evaluations (Section 3.6).

Items not meeting the in-plant screening review should be identified as outliers. Outliers require a more detailed review (see Section 6).

An analytical evaluation should also be conducted for bounding configurations/samples of duct and/or supports selected during the in-plant review. Where pressure integrity is required following an earthquake, duct and support configurations should be selected to provide representative, worst-case, bounding samples. This will typically involve a careful review of available drawings and collection of as-built information. Analysis of bounding configurations for duct and supports needing pressure boundary integrity can be used to assure performance of a larger duct population. Where structural integrity (prevention of collapse and falling) is the only concern, analysis of a random sampling of support configurations is sufficient, along with the satisfaction of the in-plant screening review requirements. If the selected configurations do not pass the analytical review, the sample population should be expanded to identify the population of HVAC system configurations that meet the required seismic criteria.

Regardless of the pressure boundary integrity requirements, the HVAC duct evaluation includes an assessment of structural integrity and potential interaction, and analysis of support configurations. If pressure boundary integrity is required, the HVAC in-plant screening review also includes requirements for duct pressure boundary assessment and a selection of bounding configurations for analysis. Items not satisfying the analytical evaluations are outliers that may require more detailed analysis or modification.

3.2 Structural Integrity Review

This section describes HVAC duct and support attributes for review during the in-plant screening review walkdowns. These attributes have led to poor seismic performance based on past earthquakes and testing (see Reference [3], Appendix A, Appendix B and Appendix D).

3.2.1 Duct Span

Duct span governs the seismic and dead load stress in the duct. Allowable duct spans and maximum cantilever lengths for applicable duct sizes must be developed prior to the in-plant screening review to enable screening of as-installed spans. The procedure for developing the allowable spans and cantilever lengths is given in Appendix C which is based on the analytical review requirements presented in Section 4.1. Lateral and vertical spans that exceed the allowable spans should be noted for further evaluation.

In addition, the following upper limits on vertical support spans apply based on review of earthquake experience data (from Reference [16]):

1. Duct support to support spans should not exceed 15 feet.
2. Supports should be provided within 5 feet from fittings such as tees and wyes in each branch of the fitting.
3. Duct cantilevered length (beyond end of last support) should not exceed 6 feet.

3.2.2 Duct Tie-downs

Ducts should be secured to their supports to preclude the possibility of displacing, falling or sliding off during a seismic event. Systems do not have to be secured to every support unless the supports are at the maximum spacing described in Section 3.2.1. The HVAC duct should be securely attached to the last hanger support at the terminal end of the duct run. Similarly, supports configured to limit the lateral movement of the HVAC duct system should also be attached to the duct. Seismic experience data indicate that a mode of failure for HVAC duct systems subject to earthquake loading is the duct falling off of end supports. An example of this occurred at the Fertimex plant during the 1985 Mexico City earthquake (Figure A-16 of Appendix A).

The SRT should use experience and judgment when evaluating where duct tie-downs are required. For example, attachment to the last support is not required if the distance from the end of the duct to the next to last support does not exceed the maximum allowable cantilever length. In this case the duct would be seismically adequate without taking credit for the last support in the duct run.

3.2.3 Duct Joints

HVAC joints should be visually inspected to verify their structural integrity. Joints (including connected tees and elbows) that are observed to be loose, incomplete, corroded, or otherwise suspect (such as those repaired with duct tape or fiberglass, or missing rivets, screws, etc.) should be reviewed in detail. Seismic experience data have shown that such joints are often the point of excessive leakage or failure of HVAC systems in an earthquake. A corroded riveted duct joint failed at the Caxton Paper Mill as a result of the 1987 New Zealand earthquake (see Appendix A, Section A.2.1). In addition, HVAC without pressure boundary requirements and with runs consisting of slip joints without pocket locks, rivets or screws should be reviewed to assure that the differential displacement between the two adjoining ducts due to seismic loading will not cause joint separation. Figure 3-1 shows different SMACNA duct joints as described in Reference [4] to aid in identifying slip-type joints.

3.2.4 Riveted Lap Joints

Round HVAC duct with light gage riveted lap joint construction should be considered outliers and subjected to more detailed investigation. The seismic experience database contains isolated cases of damage occurring to this kind of duct construction, such as the failure at the Wiltron Electronics Plant during the Morgan Hill earthquake (Figure A-4 of Appendix A). More detailed investigation should be performed to assure the seismic adequacy of this type of duct.

3.2.5 Appurtenances

Appurtenances attached to HVAC ducts must be checked to assure they will not fall in the event of an earthquake. This equipment includes items such as dampers, turning vanes, registers, access doors, filters, louvers, and air diffusers. Earthquake experience data have shown that intake and discharge screens and vanes that are inadequately attached to the duct (i.e. only slipped into place and not fastened with screws or rivets) have fallen during seismic events. Figure A-13 of Appendix A shows this type of failure. Appurtenances not positively attached to the duct that appear to be at risk of falling during an earthquake should be evaluated to determine if failure will affect the functioning of the HVAC system and whether they will become an interaction hazard with other nearby safety related equipment. Appurtenances projecting from the duct (cantilevered) should be reviewed to assure connections are seismically adequate.

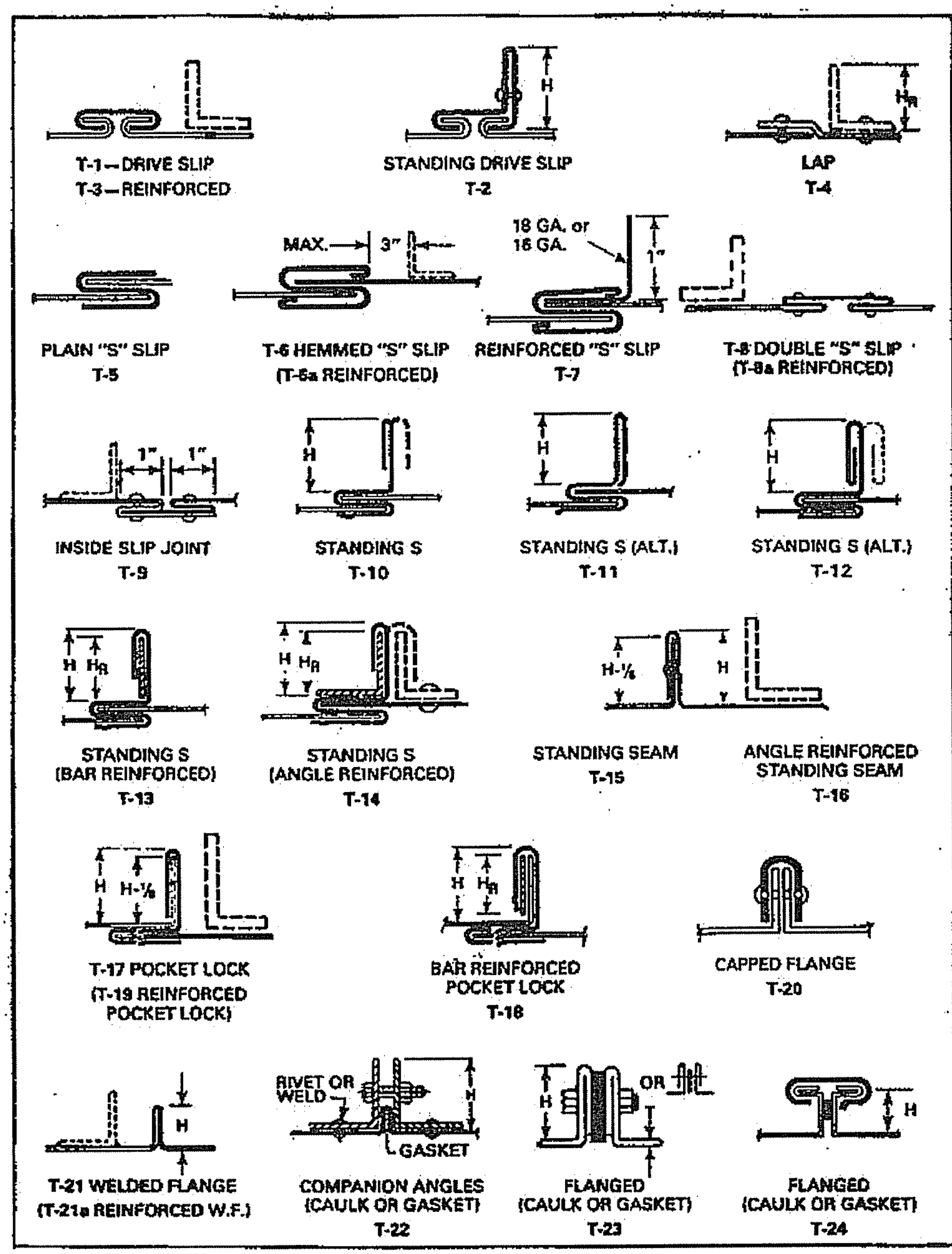


Figure 3-1
SMACNA Duct Joints

3.2.6 Flexibly Mounted Heavy Equipment

HVAC systems often have heavy pieces of mechanical equipment mounted in-line with the duct. Examples include fans, coolers, dryers, dampers with motor operators, and blowers. Earthquake experience data have shown that large pieces of equipment mounted in-line on flexible supports (e.g., without lateral and longitudinal bracing) can damage the duct from excessive displacement during an earthquake. This occurred at the Watkins-Johnson Plant during the 1989 Loma Prieta earthquake (Figure A-23 of Appendix A). Mechanical equipment should be investigated to determine if the joints connecting the equipment to the duct are sufficiently flexible to accommodate any expected swinging of the equipment during a seismic event. Potential interactions between swinging mechanical equipment and the HVAC duct or other safety related equipment should also be investigated (see Section 3.4).

Heavy equipment with connected HVAC duct may be floor-mounted on vibration isolation pads. Earthquake experience data have shown examples of excessive leakage and failures of such HVAC systems due to insufficient restraint of this equipment. Excessive leakage and failures have been caused by floor-mounted equipment falling off their isolation pads and damaging attached ducts in the process. Figure A-19 in Appendix A shows one such failure where a flexible bellows was torn due to the motion of an attached fan on vibration isolation mounts. The SQUG GIP [1] provides guidelines for seismic verification of HVAC equipment such as fans (axial and centrifugal), air handlers and chillers. Heavy equipment that is flexibly supported or on vibration isolation pads should be evaluated separately using the SQUG GIP or identified as outliers for further evaluation.

3.2.7 Branch Flexibility

Earthquake experience data have indicated that "hard points" are prone to seismic damage. Examples of hard points include locations such as wall penetrations and rigid supports on short stiff branches that are attached to flexibly supported duct. This type of seismic damage occurred at the Wiltron Electronics Plant during the Morgan Hill earthquake (Figure A-15 of Appendix A). Short, stiff branches on a flexibly supported header should be identified as outliers and checked for adequate flexibility to accommodate the expected header motion during a seismic event based on the guidelines in Section 4.1.

3.2.8 Cantilevered Duct

Earthquake experience data include isolated cases of cantilevered duct sections separating and falling from the main duct header. An example of inadequate attachment occurred at the Pacific Bell Watsonville facility during the Loma Prieta earthquake where a vertical cantilevered duct section separated and fell to the floor (Figure A-25 of Appendix A). Another example occurred at the Wiltron facility during the Morgan Hill earthquake where a vertical cantilever broke from its supporting header and fell (Figure A-14 of Appendix A). Cantilever duct sections should be adequately restrained to prevent excessive loads at the cantilever attachment point. The cantilever should be supported so that the maximum allowable cantilever length is not exceeded. Unrestrained short cantilever ducts that meet the maximum allowable cantilever length should be reviewed to insure positive attachment to the supporting headers.

3.2.9 Duct Corrosion

Excessive corrosion of HVAC ducts should be evaluated for its effect on structural integrity. Light surface corrosion is generally not a concern but heavy flaking or pitting might be. Seismic experience data have shown that significant corrosion may lead to poor seismic performance for many plant items. Corrosion reviews are especially important in damp areas of a plant such as pump houses. Evaluations should consider an estimated strength reduction due to corrosion. Significant corrosion should generally be identified for repair.

3.3 Support System Review

This section describes support attributes for review during the in-plant screening review walkdowns. These attributes have led to poor seismic performance in similar distributed type systems, such as piping, cable tray and conduit systems [1,3]. Existing duct systems judged to have similar, potentially poor seismic performance attributes, shall be documented as outliers.

3.3.1 Beam Clamps

Beam clamps should not be oriented in such a way that gravity loads are resisted only by the frictional forces developed by the clamps. Beam clamps oriented this way might loosen and slip off in an earthquake and possibly cause a collapse of the system.

3.3.2 Channel Nuts

Channel nuts used with light metal strut framing systems should have teeth or ridges stamped into the nut where it bears on the lip of the channel when slip resistance is relied upon to maintain structural integrity. Laboratory tests have shown that in a seismic environment, channel nuts without these teeth or ridges have significantly lower slip resistance capacity than those with the teeth or ridges. Excessive galvanization or loose and flaking galvanization on the strut channel may also lead to reduced bolt resistance to slippage. Channel nuts should be visually reviewed on a random basis to provide reasonable assurance that teeth or ridges are present when required for structural integrity, and that the nuts are properly engaged on the frame sections.

3.3.3 Cast Iron Anchor Embedment

Threaded rod hanger anchor embedments constructed of cast iron should be evaluated because of potential brittle failure modes. Plant documentation should be consulted to determine whether anchor embedments are cast iron. Earthquake experience data includes examples where heavily loaded rod hangers threaded into cast-iron inserts have failed [8]. Failure modes include anchor pullout and anchor fracture where rods are only partially threaded into the anchor.

3.3.4 Broken Hardware

Any observed missing or broken hardware for HVAC duct and supports should be noted so that repair or replacement may be provided. This includes examples such as missing nuts or bolts on connections, bent or damaged support members, dented duct seams, separated duct joints, torn expansion joints and similar defects. HVAC related hardware that is missing or broken should be evaluated to determine the consequences that this would have on the HVAC system. In particular, it should be determined if the integrity of the HVAC pressure boundary could be affected.

3.3.5 Support Corrosion

Excessive corrosion of HVAC duct supports and support components (including anchorage) should be evaluated for its effect on structural integrity. Light surface corrosion is generally not a concern but heavy flaking or pitting might be. Seismic experience data have shown that significant corrosion may lead to poor seismic performance for many plant items. Evaluations should consider the effects of an estimated strength reduction or loss of support due to corrosion. Significant corrosion should generally be identified for repair.

3.3.6 Concrete Quality

Gross defects or large cracks in the concrete to which the duct supports are attached should be evaluated for their potential effects on seismic performance. Visibly large cracks, significant spalled concrete, and serious honeycombing in the vicinity of HVAC duct support anchors should be considered as gross defects. The walkdown team should consider grossly defective concrete areas as outliers and include supports anchored to marginally defective concrete in the sample selected for the limited analytical review.

3.3.7 Welded Attachments

Support connections containing obviously undersized welds, incomplete welds, or welds of poor quality (i.e., with significant burn-through) require analytical review incorporating reduced capacities. Seismic experience data and shake table tests have shown that welds not capable of developing the strength of connected members may be subject to a brittle-type failure mode during seismic loading.

3.3.8 Rod Hanger Fatigue

Although no specific instance of fatigue failure has been identified for HVAC duct rod hangers, raceway shake table tests have shown that short, fixed ended, heavily loaded rod hangers may be subject to low cycle, high strain fatigue failures during seismic events [1 and 8]. Rod hangers that may be subject to high strain low cycle fatigue effects should be investigated in greater detail. The rod fatigue evaluation requirements outlined in Section 4.4.2 should be used to address rod fatigue concerns.

Rods to be evaluated are characterized as follows:

- Rods double nutted to flanges of steel members
- Rods threaded into shell-type concrete expansion anchors
- Rods connected by rod couplers to non-shell type concrete expansion anchors
- Rods threaded into rod couplers which are welded to overhead steel embedments.

3.4 Seismic Interaction Review

The HVAC duct system must be reviewed for seismic interactions. The walkdown team should be aware of issues associated with seismic interaction and be alert for potential seismic interaction hazards. Only credible and significant interaction sources should be considered as outliers. Damage that may occur to the duct itself as well as to any safety related equipment that the duct may interact with should be considered. Detailed guidance on identifying and evaluating seismic interactions is given in Appendix D of Reference [1].

3.4.1 Proximity and Falling Hazards

Seismic interactions may occur as a result of movement of the HVAC duct and/or movement of adjacent plant commodities. The range of motion of the HVAC duct system, and those components in the vicinity that may come into contact with the duct system, must be assessed. Reference [16] recommends that displacement of unbraced HVAC duct systems be estimated as the in-structure 7% damped spectral displacement corresponding to the support system's free-swinging pendulum frequency. For braced duct systems, Reference [16] recommends that a resonant frequency of 10 Hertz be assumed to achieve an upper bound estimate for the displacement.

Duct systems attached to or in the vicinity of unanchored components or unreinforced block walls could be damaged by the sliding/falling of the component or failure and falling of the block wall. Such instances should be noted, and the stability of the component or block wall evaluated.

3.4.2 Flexibility of Attached Lines

Distribution lines such as small bore piping, tubing, conduit or cable that are connected to dampers can potentially fail if there is insufficient flexibility to accommodate relative motion between the damper and the adjacent equipment or structures. Straight, in-line connections in particular are prone to seismic damage or failure. The walkdown team should review distribution lines connected to dampers to insure there is adequate flexibility between the damper and the first support on the building or nearby structure.

3.4.3 Differential Displacement Hazards

Ducts spanning from one structure to another should be checked to assure that they can accommodate any relative movement of the structures. Experience data indicate there can be excessive leakage or failures for duct systems without sufficient flexibility at spans experiencing differential displacement [3]. If this condition is identified, stress criteria established in Section 4 of this report should be used.

3.5 Pressure Boundary Integrity Review

This section applies to HVAC duct systems where a high confidence level of pressure boundary integrity is required for functional considerations. Examples where pressure boundary integrity may be required include the following:

- Systems with little or no margin for airflow
- Systems where leakage could significantly change system balance
- Systems that separate clean from potentially contaminated or hazardous material (such as battery room exhaust).

The following are in-plant screening requirements to achieve a high level of confidence of pressure boundary integrity.

3.5.1 Duct Joints and Stiffener Spacing

Stiffeners prevent bulging of the duct panels due to internal pressure. Lateral joints such as companion angles, and lateral reinforcements, typically of steel angles, are considered as stiffeners. Earthquake experience and test data have demonstrated that duct systems that met the SMACNA guidelines performed well during earthquakes. Items to be checked for the given system operating pressure requirements include sheet metal gage, stiffener size and spacing, and panel dimensions. For bolted duct connections, it is also necessary to check minimum flange height, number of bolts, maximum hole spacing, and ring size where segments of round duct are bolted together. Applicable sections from the SMACNA standards include Section 7 of Reference [6], Chapters 4 and 12 of Reference [7], and Chapters 1 and 3 of Reference [5].

3.5.2 Round Duct Supports

Round HVAC duct runs supported such that the duct is point loaded should be considered outliers unless the duct is reinforced at the point of support. An example of this situation is a round duct supported by a rod hanger without a saddle.

3.5.3 Flexible Bellows

Flexible bellows connecting HVAC duct to in-line equipment may become damaged if they do not have enough slack to accommodate differential motion between the equipment and the duct. Bellows are typically not designed to resist any large differential motions imposed by the earthquake. If reasonable estimates of bellows flexibility cannot be determined by judging the available slack in the as-installed configuration, then manufacturer's data should be reviewed.

3.6 Selection of Bounding Configurations

As part of the in-plant screening review, representative, worst-case HVAC duct and duct supports should be selected as bounding configurations. The extent of the sample should be determined by the Seismic Capability Engineers based on the diversity, complexity and extent of the systems being reviewed. The samples should include representative samples of the major different types of duct and duct supports for the HVAC duct and damper systems being reviewed. As a general guideline, 10 to 20 different sample supports and 1 to 4 sample duct runs should be selected for facilities evaluating multiple HVAC systems. These selected configurations should be evaluated using the analytical review criteria in Section 4. Detailed evaluation of bounding, worst-case configurations assures the seismic adequacy of the entire population. When selected configurations do not pass the analytical review, the selected population should be expanded to identify the population of HVAC system configurations that meet the required seismic criteria. For example, all supports and duct runs that are represented by the item that failed should be located and identified for modification or further (more detailed) review.

The procedure for the selection of boundary configurations for duct and support system analytical review is dependent upon the functional requirements of the system. For duct systems requiring structural integrity or reasonable assurance for pressure boundary integrity (where potential small tears or leaks are acceptable), the sample selection only needs to include worst-case bounding duct *supports*. For systems where full pressure boundary integrity is required, the worst-case bounding sample should include the *duct* run itself as well as the *supports*.

The walkdown team needs to understand the analytical review requirements presented in Section 4 prior to performing in-plant screening reviews and selection of bounding configurations. The goal is to establish a biased, worst-case sampling, representative of and bounding the major different HVAC configurations in the plant. This bounding of worst-case samples will be subject to analytical review.

Notes should be taken describing the basis for selection of each configuration. The location of the selected configuration should be noted, and detailed sketches of the as-installed condition should be made. As-built sketches should include the duct and support configuration, dimensions, connection details, anchorage attributes, member sizes, and loading. Any additional information that may be considered relevant to the seismic adequacy of the selected configuration should be noted in detail.

Building elevation should be taken into account when choosing HVAC duct configurations as bounding samples. Identical systems at two different elevations in the plant experience different seismic environments. The higher the building elevation, the greater the seismic demand. Therefore, it is possible that a system appearing to have few seismic vulnerabilities which is located at an upper elevation in a building may actually have a greater probability of failure than a system located at a lower elevation with a worse configuration. The walkdown team members should acquaint themselves with the differing seismic demand environments in the buildings being inspected by reviewing the floor response spectra before selecting the bounding sample.

3.6.1 Selecting Bounding Duct Support Samples

The most heavily loaded support for each duct configuration should be selected as a bounding case. Long spans, insulated duct, supports carrying multiple ducts, top supports of vertical runs, heavy in-line components and isolated "stiff" supports on rod hung systems are indicators of heavy load. Duct support configurations to consider are long HVAC runs with few supports providing lateral or longitudinal restraint, long vertical runs, runs with seemingly weak curved sections, and runs with large, flexibly mounted in-line equipment. Of particular importance are duct supports that appear to have more loading than originally designed for. Heavily loaded supports can be identified by the presence of other plant components attached to the supports, such as supports for pipe, cable trays, and conduit.

Selection of a bounding duct support should consider conditions where anchorage appears to be the weak link in the load path. Duct supports with anchorage that appears marginal for the supported weight should be investigated. Anchorage with undersized welds, incomplete welds, or welds of poor quality should also be evaluated. Overhead support steel, such as steel angle, used specifically as an anchor point to support the duct system should have its anchorage to the building structure evaluated.

3.6.2 Selection of Bounding Duct Configurations

When appropriate, the selection should include duct systems with evidence of extreme or over-pressure loads, and/or duct systems that appear to have unusual loading conditions. Examples include duct runs that support other equipment items (such as raceways or piping), ducts that are shielded, heavily insulated or covered with fireproofing, and ducts with suspect flexible joints.

4

ANALYTICAL REVIEW CRITERIA

4.1 Overview of Analysis Criteria

Analytical evaluations shall be performed on the selected bounding or sample HVAC duct and support configurations required to achieve duct system function following a seismic event. The selection of duct and/or support configurations shall be consistent with the requirements of Section 3.6. The duct evaluation criteria are based primarily on the design approach utilized in SMACNA's construction standards for round and rectangular industrial duct [6, 7]. Equations for computing pressure stresses in duct and stiffeners are taken directly from SMACNA standards. Use of this procedure results in a conservative estimate of the true duct capacity and is compatible with test data from References [9] through [13].

The pressure boundary integrity review of HVAC duct considers the combined effects of pressure, dead weight and seismic loads on the duct. The combined dead load and seismic stress is checked against a factored allowable working stress for acceptance. The general stress combination equations are given below:

Horizontal Rectangular Duct

$$f_{DL} + [(EQ_v)^2 + (EQ_h)^2]^{0.5} < 1.7\ F_b \qquad \textbf{Eq. 4-1}$$

Vertical Rectangular Duct

$$[(EQ_{h1})^2 + (EQ_{h2})^2]^{0.5} < 1.7\ F_b \qquad \textbf{Eq. 4-2}$$

Horizontal Circular Duct

$$f_{DL} + EQ_v < 1.7\ F_b \qquad \textbf{Eq. 4-3}$$

$$EQ_h < 1.7\ F_b \qquad \textbf{Eq. 4-4}$$

Vertical Circular Duct

$$EQ_h < 1.7\ F_b \qquad \textbf{Eq. 4-5}$$

Pressure Stress

$$f_p < F_p$$ **Eq. 4-6**

Where:

f_{DL} = Dead load bending stress
f_p = Pressure stress
EQ_v = Bending stress resulting from DBE seismic loads in the vertical direction
EQ_h = Bending stress resulting from DBE seismic loads in the horizontal transverse direction. The additional subscripts 1 and 2 refer to stress components from two orthogonal transverse seismic loading conditions
F_b = Bending stress allowable (normal working stress allowable)
F_p = Pressure stress allowable (normal working stress allowable)

The 1.7 increase in allowable stress accounts for the short duration of seismic loading. This increase is consistent with realistic allowable capacities for cable tray support components in Section 8.3.8 of Reference [1].

The effect of longitudinal seismic loading on the ducts is typically not significant since these forces are usually distributed over many support points. The effects of longitudinal seismic loading should be combined with transverse and vertical seismic loading by the Square Root of the Sum of the Squares (SRSS) method in the stress calculations.

4.2 Dead Load and Seismic Stress

Analysis for dead and seismic loads may be performed using either the equivalent static load method or the response spectrum method.

The equivalent static load method follows a tributary length approach using the spectral acceleration at the applicable frequency (use peak floor spectral acceleration if frequency is unknown). An equivalent static coefficient of 1.0 times the spectral acceleration is used which is similar to the static coefficient used for equipment items addressed in Reference [1]. For this method, the bending moment is approximated by [6, 7]:

$$M = \frac{w\ell^2}{8} \text{ (For ducts spanning over one or two spans)}$$ **Eq. 4-7**

$$M = \frac{w\ell^2}{10} \text{ (For ducts spanning over 3 or more supports)}$$ **Eq. 4-8**

where:

- w = applied linear load (lb/in)
- ℓ = tributary span (in)
- M = duct bending moment (in-lb)

Other configuration anomalies, such as cantilevered duct sections, shall be considered on a case-by-case basis.

Bending stresses due to axial response of a duct system may result if the axial run of duct is not braced in the longitudinal direction along the run of duct. If the axial restraint is provided by the first lateral restraint around a bend in the system, then the bending stress in the duct at the lateral restraint should be checked also for longitudinal motion of a tributary span of the axial run.

Alternatively, longitudinal load resistance along an axial run may be provided by framing action between the duct itself and the supports if the duct is adequately attached to the supports. In this case, the additional bending moment in the duct (about the transverse horizontal axis) must be checked.

The response spectrum method requires modeling of sufficient ducting to analytically represent the expected dynamic response of the system. In general, this includes duct up to anchor points or equivalent restraint. Modal combinations are performed using the Square Root of the Sum of the Squares (SRSS) method. The analyses should consider all modes up to 33 Hz and include a minimum 90% mass participation.

For both methods, a critical damping ratio of 7% is appropriate for determining the seismic loads. This damping ratio is a conservative estimate of derived damping ratios from actual shake table tests [9 through 13].

Bending stresses for dead weight and seismic loads are derived using the duct section modulus as follows:

$$f_b = \frac{M}{Z} \qquad \textbf{Eq. 4-9}$$

where:

- f_b = Bending stress (psi)
- M = Applied bending moment (in-lb)
- Z = Duct section modulus (in^3)

For rectangular ducts, Reference [6] limits the effective area of sheet metal for calculation of the duct section modulus to a 2-inch by 2-inch region at the four corners of the duct. A reduced section modulus is thus calculated by assuming only these corners are effective in resisting bending. For round ducts, the full section is available for resisting the bending moment on the duct [7].

In addition, frequency correction factors of 0.59 and 0.87 for pocket lock and companion angle constructions, respectively, must be applied to adjust the calculated rectangular duct frequency based on analytical correlation of test results (Appendix D). Duct joints that do not fit any of the Figure 3-1 duct joint types and cannot be shown to behave in a manner equivalent to one of them should be evaluated separately.

Allowable bending stresses differ for rectangular and round ducts, as detailed in the following sections.

4.2.1 Allowable Bending Stress for Rectangular Ducts

The allowable bending stress for normal operating conditions as specified by SMACNA [6], is 8 ksi for carbon steel, galvanized sheet and stainless steel materials. This corresponds to 0.27 times the minimum yield strength of 30 ksi for typical materials used for industrial duct construction, within the specified temperature range.

The SMACNA standard for rectangular industrial duct construction [6] does not include design of duct fabricated of aluminum. A reasonable allowable bending stress for normal operating conditions for aluminum may be taken as 4.9 ksi. This corresponds to 0.27 times the minimum yield strength of 21 ksi for aluminum materials, times a yield strength reduction factor of 0.86 for temperatures up to 300 degrees Fahrenheit.

The normal allowable bending stress for rectangular ducts may be increased by a factor of 1.7 for DBE loads as detailed at the beginning of Section 4. This increase may be taken for ducts having pocket lock and companion angle (or equivalent) joints. This applies to joint types T-1 through T-3 and T-15 through T-24 of Figure 3-1, since Appendix D tests were performed on joints that are structurally similar to these types of duct joints. The normal allowable stress should not be increased by 1.7 for DBE for ducts with potentially weaker joints that rely on friction or crimping. Joints such as types T-4 through T-14 of Figure 3-1 are examples of potentially weaker joint types.

Duct joint that do not fit any of the Figure 3-1 duct joint types and cannot be shown to behave in a manner equivalent to one of them should be evaluated separately.

4.2.2 Allowable Bending Stress for Circular Ducts

The allowable bending stress for circular ducts as specified by SMACNA [7] depends on the duct materials, operating temperature and diameter to thickness ratio.

The normal allowable bending stress for hot rolled carbon steel (based on a minimum yield stress of 33 ksi and maximum temperature of 400 degrees Fahrenheit) is as follows:

$$F_b = 10.7 \text{ ksi} \qquad \text{for } D/t < 294 \text{ (hot rolled carbon steel)}$$

$$F_b = \frac{3140}{D\ t} \text{ ksi} \qquad \text{for } D/t \geq 294 \text{ (hot rolled carbon steel)}$$

where:

D = Diameter of circular duct (in)
t = Duct thickness (in)
F_b = Bending stress allowable (normal working stress allowable)

The normal allowable bending stress for cold rolled carbon steel and galvanized sheet (based on a minimum yield stress of 32 ksi and maximum temperature of 400 degrees Fahrenheit is as follows:

$$F_b = 11.0 \text{ ksi} \qquad \text{for } D/t < 285 \text{ (cold rolled carbon steel, galvanized sheet)}$$

$$F_b = \frac{3140}{D\ t} \text{ ksi} \qquad \text{for } D/t \geq 285 \text{ (cold rolled carbon steel, galvanized sheet)}$$

The normal allowable bending stress for stainless steel is as follows. The following are minimum values that envelope parameters given in the SMACNA standard [7] for types of stainless steel typically used for duct. These values assume minimum yield strength of 30 ksi and maximum temperature of 400 degrees Fahrenheit. Higher allowable stress values may be obtained from Reference [7] for materials with a higher minimum yield strength and lower temperature, based on more detailed analysis.

$$F_b = 8.8 \text{ ksi} \qquad \text{for } D/t < 113 \text{ (stainless steel)}$$

$$F_b = \frac{993}{D/t} \text{ ksi} \qquad \text{for } D/t \geq 113 \text{ (stainless steel)}$$

The normal allowable bending stress for aluminum is as follows. The following are minimum values that envelope parameters given in the SMACNA standard [7] for types of aluminum typically used for duct. These values assume a minimum yield strength of 21 ksi and maximum temperature of 300 degrees Fahrenheit. Higher allowable stress values may be obtained from Reference [7] for materials with a higher minimum yield strength and lower temperature, based on more detailed analysis.

$$F_b = 6.0 \text{ ksi} \qquad \text{for } D/t < 110 \text{ (aluminum)}$$

$$F_b = \frac{662}{D/t} \text{ ksi} \qquad \text{for } D/t \geq 110 \text{ (aluminum)}$$

The normal allowable bending stress for round ducts may be increased by a factor of 1.7 for DBE loads as detailed at the beginning of Section 4. This increase may be taken for ducts having pocket lock and companion angle (or equivalent) joints. This applies to joint types T-1 through T-3 and T-15 through T-24 of Figure 3-1, since Appendix D tests were performed on joints that are structurally similar to these types of duct joints. The normal allowable stress should not be increased by 1.7 for DBE for ducts with potentially weaker joints such as types T-4 through T-14 of Figure 3-1. These joints are potentially weaker because they rely on friction or crimping to transfer force across the joint.

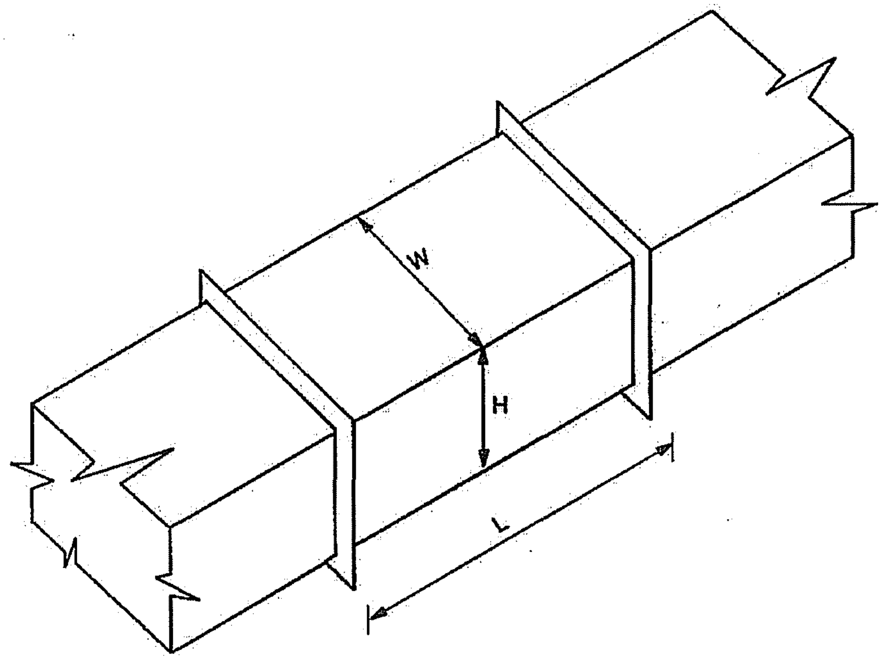
4.3 Pressure Stress in Ducts

The effect of stress in HVAC duct material from internal pressure shall be accounted for in the analytic evaluation of HVAC duct requiring pressure boundary integrity. These pressure stresses are checked against pressure stress allowables established in the SMACNA guidelines.

4.3.1 Pressure Stresses in Rectangular Ducts

The SMACNA design of rectangular ducts is based on simplifying assumptions which permit the reduction of the analysis from a three-dimensional to a two-dimensional problem. Each of the four sides of the duct is assumed to act as an independent two-dimensional panel. Duct panel stresses are computed based on thin plate bending equations found in Reference [15].

For a given rectangular duct, the largest cross-sectional dimension (i.e. width or height) is used for stress analysis (see Figure 4-1). The applicable plate bending equations are dependent on the ratio of this maximum duct dimension, *S*, to the duct stiffener spacing, L.



S = Max (H, W)

Figure 4-1
Rectangular Duct Configuration

Two simplified models are used to calculate duct pressure stresses. The following notations are used:

H	=	Height of duct (in)
W	=	Width of duct (in)
S	=	Max (H, W) (in)
L	=	Stiffener spacing (in)
t	=	Duct thickness (in)
E	=	Young's Modulus of duct material (psi) adjusted for temperature. Use 9.5×10^6 psi for stainless steel, and 9.2×10^6 psi for aluminum. Slightly higher values may be obtained using more detailed analysis from Reference [7].
ν	=	Poisson's ratio (dimensionless), taken as 0.30 for all duct materials
p	=	Applied pressure (psi)

If $L \leq S$:

The duct panel is idealized as one-way plate bending over a fixed-ended span, L, with axial in-plane tensile reactions resisting the increase in panel length due to bending curvature.

Let:

T = Axial tensile reaction resisting the increase in length due to bending curvature

D_b = $E\,t^3/(12(1-\nu^2))$ (plate bending stiffness coefficient) **Eq. 4-10**

u = $0.5L(T/D)^{0.5}$ **Eq. 4-11**

To obtain u, use Figure 4-2 taken from Reference [15]. To use this chart, the variable U_1 is first calculated as:

U_1 = $(E^2\,t^8)/((1-\nu^2)^2\,p^2\,L^8)$ **Eq. 4-12**

The quantity $\log_{10}(10^4\,U_1^{0.5})$ then gives the ordinate of the curve in Figure 4-2, and the corresponding abscissa gives the required value of u. After determining U, the maximum stresses in the plate are calculated as follows:

The maximum tensile stress is [15]:

$f_1 = (E\,u^2)\,(t/L)^2/(3(1-\nu^2))$ **Eq. 4-13**

The maximum bending stress is [15]:

$f_2 = (p/2)(L/t)^2\,(3u-\tanh(u))/(u^2\,\tanh(u))$ **Eq. 4-14**

Maximum total pressure stress is:

$f_p = f_1 + f_2$ **Eq. 4-15**

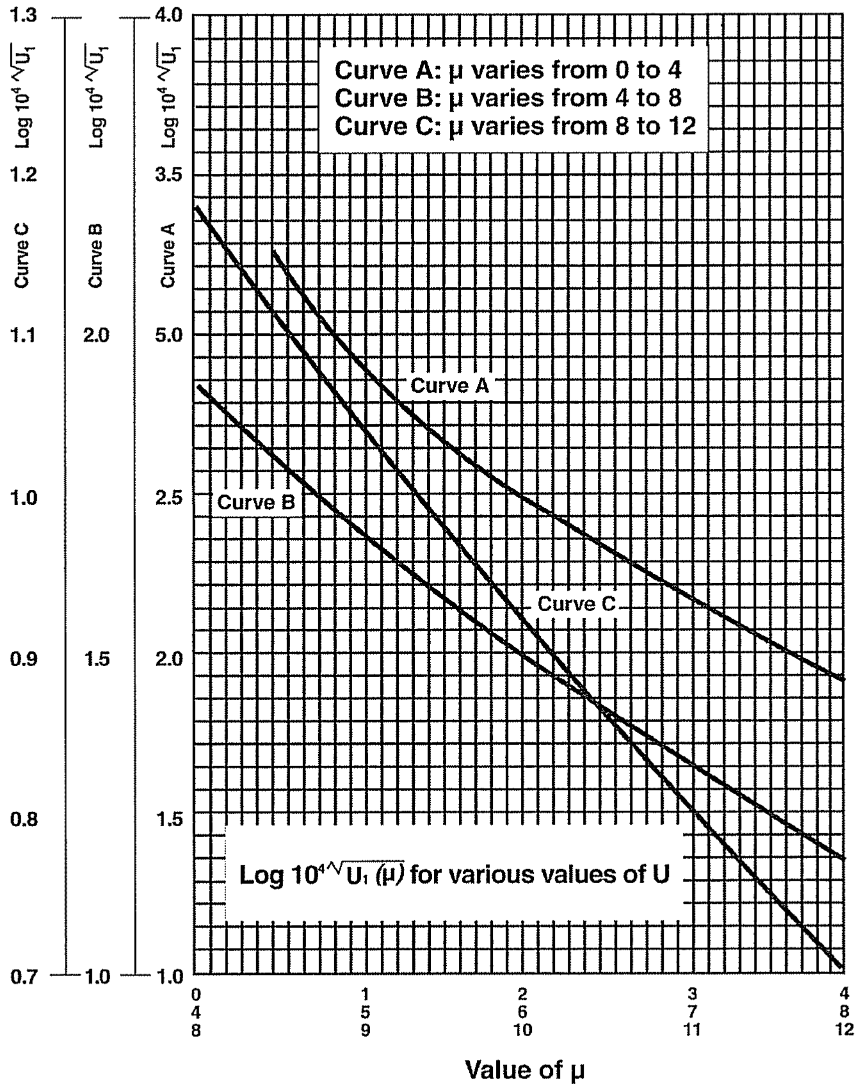


Figure 4-2
Value of u for Rectangular Ducts [15]

If L > S:

As the stiffener spacing exceeds the width of the critical duct section, the restraining effect of the panel side edges increasingly influences the stress distribution within the panel, requiring the use of a second set of stress equations.

The panel is modeled as a uniformly loaded rectangular two-way plate fixed on the two opposite edges at the stiffeners and hinged on the edges along the sides. The maximum bending moment occurs at the mid-points of the fixed edges and is given by [15]:

$$M_{max} = K\, p\, S^2 \qquad \textbf{Eq. 4-16}$$

A list of K values for various L/S ratios, is given in Table 4-1.

Table 4-1
Value of K for Rectangular Ducts [15]

Values of Parameter K			
L/S	**K**	**L/S**	**K**
1.0	-0.0697	1.7	-0.1090
1.1	-0.0787	1.8	-0.1122
1.3	-0.0868	1.9	-0.1152
1.4	-0.0938	2.0	-0.1174
1.5	-0.0998	3.0	-0.1191
1.6	-0.1049	---	-0.1250

The resulting stress is:

$$f_p \quad = \quad 6\,K\,p\,S^2/t^2 \qquad \textbf{Eq. 4-17}$$

Through the use of equations Eq. 4-16 and Eq. 4-17, the panel pressure stresses can be calculated for any combination of system pressure and duct dimensions.

The allowable pressure stress for rectangular carbon steel, galvanized sheet and stainless steel ducts is taken from Reference [6] as:

F_p = 24 ksi (carbon steel, galvanized sheet and stainless steel)

The allowable pressure stress for aluminum ducts may be taken as:

F_p = 15 ksi (aluminum)

4.3.2 Pressure Stresses in Round Ducts

The pressure capacity of circular ducting is controlled by either buckling of the duct 'skin' or buckling (or yielding) of the duct stiffeners assuming negative duct pressure. Duct skin buckling is influenced by the duct end conditions. The following notations are used:

D = Duct diameter (in)
L = Stiffener spacing (in)
t = Duct skin thickness (in)
P_n = Critical duct pressure (psi)
ℓ_c = Critical stiffener spacing (in)

The critical duct pressure as determined in Reference [7] is dependent on the spacing of the stiffeners. The critical spacing of the stiffness is defined as the spacing beyond which the duct is regarded as unstiffened, because the stiffeners are no longer contributing to the capacity of the duct to resist negative pressure. The critical spacing is as follows:

$$\ell_c = 1.115\,D\sqrt{D/t}$$ **Eq. 4-18**

When the circumferential stiffener spacing is less than critical spacing, the allowable duct pressure is as follows:

$$P_n = 18.1\text{x}10^6\,(t/D)^{2.5}(D/L)\text{ psi (carbon steel, galvanized sheet)}$$ **Eq. 4-19**

$$P_n = 16.1\text{x}10^6\,(t/D)^{2.5}(D/L)\text{ psi (stainless steel)}$$ **Eq. 4-20**

$$P_n = 5.6\text{x}10^6\,(t/D)^{2.5}(D/L)\text{ psi (aluminum)}$$ **Eq. 4-21**

When the duct is unstiffened or when the circumferential stiffener spacing is greater than the critical spacing, the maximum duct pressure is as follows:

$$P_n = 16.2\text{x}10^6\,(t/D)^3\text{ psi (carbon steel, galvanized sheet)}$$ **Eq. 4-22**

$$P_n = 14.5\text{x}10^6\,(t/D)^3\text{ psi (stainless steel)}$$ **Eq. 4-23**

$$P_n = 5.1\text{x}10^3\,(t/D)^3\text{ psi (aluminum)}$$ **Eq. 4-24**

These formulas are valid for carbon steel, galvanized sheet steel and stainless steel up to 400 degrees Fahrenheit and for aluminum up to 300 degrees Fahrenheit. They are based on temperature adjusted Young's Moduli of $29.5\text{x}10^6$ psi for carbon steel and galvanized sheet steel, $26.3\text{x}10^6$ psi for stainless steel, and $9.2\text{x}10^6$ psi for aluminum. Slightly higher values for pressure may be obtained for specific stainless steel and aluminum materials at lower temperatures by using more detailed analysis from Reference [7].

The critical duct pressure should be used as the pressure stress allowable, F_p, and compared with the actual pressure.

4.4 Pressure Stresses in Stiffeners

4.4.1 Stiffener Evaluation for Rectangular Ducts

Let:

q	=	Tributary load to stiffener (lb/in)
p	=	Duct pressure (psi)
H	=	Height of duct (in)
W	=	Width of duct (in)
S	=	Max (H, W)
L	=	Stiffener spacing (in)
$F_{b(STIFF)}$	=	Allowable bending stress in the stiffener (ksi)

Following analysis of the panels, the duct stiffeners are checked for two conditions:

- Maximum deflection $\leq S/360$
- Maximum bending stress in the stiffener $\leq F_{b(STIFF)}$

The load transmitted to the stiffener from the duct panel is dependent on the ratio of L/S. The tributary load to the stiffener, q, is calculated as follows:

For $L/S \leq 2.0$,

$$q = p\,L \qquad \textbf{Eq. 4-25}$$

For $2.0 < L/S \leq 10.0$,

$$q = p(1.25 - 0.125\,L/S)\,L \qquad \textbf{Eq. 4-26}$$

For $L/S \geq 10.0$,

q = tributary load resulting from pressure p being applied on an area bounded by lines radiating at 45° from the ends of the stiffener (see Figure 4-3).

$$= p(S/2) \qquad \textbf{Eq. 4-27}$$

The stiffener stress evaluation for the above loading conditions is dependent upon whether the stiffener ends are fixed or pinned.

Stiffeners welded at their ends to stiffeners from the adjacent side of the duct provide bending moment transition and are considered fixed. Such stiffeners should be analyzed as follows:

$$f = q\ S^2\ c/(10\ I) \leq F_{b(STIFF)}$$ **Eq. 4-28**

$$d = 3q\ S^4/(384\ E\ I) \leq S/360$$ **Eq. 4-29**

where:

I	=	Moment of inertia of the stiffener (in^4)
c	=	Distance between neutral axis and extreme fiber of stiffener (in)
E	=	Young's Modulus of stiffener (psi) adjusted for temperature. Use 29.5×10^6 psi for stainless steel, and 9.2×10^6 psi for aluminum. Slightly higher values may be obtained using more detailed analysis from Reference [7].
d	=	maximum stiffener displacement (in)

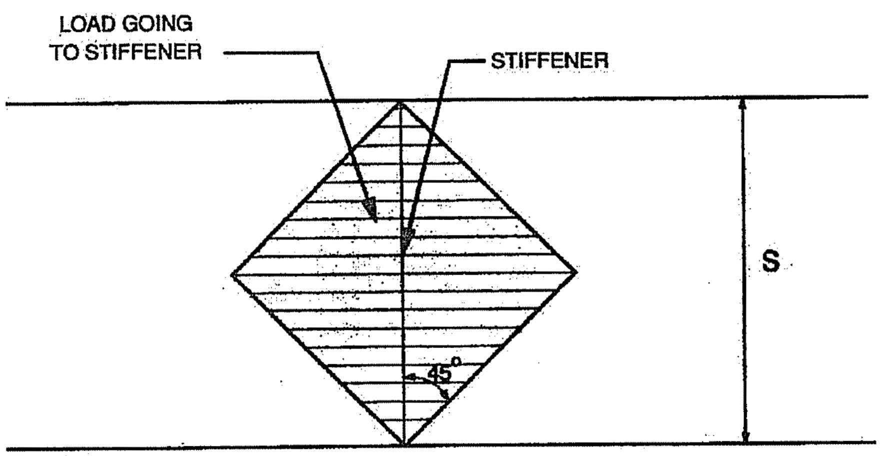


Figure 4-3
Load Going to Stiffener on a Rectangular Duct When *L/S* ≥ 10.0 [6]

Stiffeners are considered pinned regardless of whether they are bolted at their ends, tack welded, or not connected at their ends. Such stiffeners should be evaluated as follows:

$$f = q\ S^2\ c/(8\ I) \leq F_{b(STIFF)}$$ **Eq. 4-30**

$$d = 5q\ S^4/(384\ E\ I) \leq S/360$$ **Eq. 4-31**

The allowable bending stress in the stiffener is set as follows:

$F_{b(STIFF)}$ = 24 ksi (Carbon steel, galvanized sheet steel)

$F_{b(STIFF)}$ = 19.2 ksi (Stainless steel)

$F_{b(STIFF)}$ = 13.1 ksi (Aluminum)

Inadequate stiffeners will need to be supplemented. Stiffeners placed on only two opposite sides of a rectangular duct and meeting the above criteria are adequate as long as the panel width is less than 72 inches. For panels of longer size, stress concentration becomes excessive and additional stiffeners are required.

4.4.2 Stiffener Evaluation for Round Ducts

The capacity of round duct stiffeners is controlled by buckling or yielding, where the theoretical buckling strength is proportional to the moment of inertia of the stiffener, and the yield strength is proportional to the area. Both of the following equations for moment of inertia and stiffener area for the respective material type must therefore be satisfied [7].

$I_s > I_{MIN} = 1.6\text{x}10^{-8}\ L\ D^3\ P_\eta$ (Carbon steel, galvanized sheet steel) **Eq. 4-32**

$I_s > I_{MIN} = 1.7\text{x}10^{-8}\ L\ D^3\ P_\eta$ (Stainless steel) **Eq. 4-33**

$I_s > I_{MIN} = 5.0\text{x}10^{-8}\ L\ D^3\ P_\eta$ (Aluminum) **Eq. 4-34**

$A_s > A_{MIN} = 6.3\text{x}10^{-5}\ L\ D\ P_\eta$ (Carbon steel, galvanized sheet steel) **Eq. 4-35**

$A_s > A_{MIN} = 7.6\text{x}10^{-5}\ L\ D\ P_\eta$ (Stainless steel) **Eq. 4-36**

$A_s > A_{MIN} = 10.8\text{x}10^{-5}\ L\ D\ P_\eta$ (Aluminum) **Eq. 4-37**

where:

I_s = Moment of inertia of stiffener (in^4)
A_s = Area of stiffener (in^2)
P_η = Applied pressure in duct (psi)
L = Stiffener spacing (in)
D = Duct diameter (in)

Higher values may be obtained for specific materials and for lower temperatures by using more detailed analysis from Reference [7].

4.5 Duct Support Evaluation

4.5.1 Metal Frame and Anchorage

The selection of support configurations for evaluation shall be consistent with the requirements of Section 3.6. Simplified support evaluation requirements, consistent with those presented in Section 8 of Reference [1] for limited analytical review of raceway supports, are applicable for the seismic adequacy verification of duct supports. These include the following checks, applying to both the support structural framing and the anchorage to the building structure:

Dead load

Vertical capacity (for greater of 5g or 6 ZPA_h times Dead Load)

Ductility

Lateral load check

Longitudinal load check

Rod hanger fatigue evaluation

The 5 times dead load check is used in the vertical capacity check accounts for the dynamic characteristic differences in terms of system damping between the HVAC duct and raceway systems. That is, the 3 times dead load check established for raceways is factored up by the difference in spectral acceleration demand due to the lower damping in HVAC systems (on the order of 7%) as compared to raceway systems damping (on the order of 15%). The 6 times ZPA_h check, where ZPA_h is the zero period acceleration at the support anchor, is from Reference [16]. This controls when ZPA_h exceeds 0.83g.

A discussion of the requirements for the dead load check, vertical capacity check, ductility review, lateral and longitudinal loads checks is included in Appendix F. The rod hanger fatigue evaluation guidelines are presented in Appendix E.

For systems in which detailed modal response spectrum analysis is performed, the duct support frame should be evaluated for the resulting seismic loads combined with dead loads. Loads from other attached systems, such as conduit or piping, should also be considered. All steel components such as bracket members, support members, and internal support framing connections should be checked, using allowables as defined in Part 1 of the AISC [2].

The buckling analysis of vertical support members and lateral bracing should also follow the criteria of Part 1 of AISC [2]. It is recognized that many support configurations have structurally redundant members. If buckling is predicted to occur in a support member, the support may still be acceptable if the buckling does not affect the overall stability of the duct system. For example, if a lateral brace is found to buckle under imposed seismic loading, but vertical capacity is not jeopardized, the duct can be analyzed ignoring the presence of the brace. If the duct system stresses are acceptable without the lateral brace and spatial (proximity-related) interaction due to duct seismic displacement is not a problem, then the support is acceptable.

4.5.2 Rod Hanger Fatigue Evaluation

Short, fixed ended, heavily loaded rod hangers may be subject to low cycle, high strain fatigue failures during seismic events [8]. Rod hangers of concern are typically of fixed end connections. These rods are characterized as follows:

- Rods double-nutted to flanges of steel members
- Rods threaded into shell-type concrete expansion anchors
- Rods connected by rod couplers to non-shell type concrete expansion anchors
- Rods threaded into rod couplers welded to overhead steel embedments

Rod hangers that may be subject to high strain low cycle fatigue effects should be investigated in greater detail. The rod fatigue evaluation guidelines outlined in Attachment E should be used to address any rod fatigue concerns.

4.5.3 Anchorage Capacity

Capacity values for anchors should be taken from Reference [1]. The provisions of these anchorage guidelines should be followed, including edge distance, bolt spacing, and inspection procedures. Tightness checks are not required for expansion anchor bolts that are normally subjected to tensile forces due to dead weight, since the adequacy of the anchorage set is effectively proof tested by the dead weight loading. This applies to expansion anchors for overhead and wall mounted supports.

4.5.4 Redundancy and Consequence Test

Isolated cases of a support not meeting the analytical review guidelines may be accepted if the HVAC support system has redundancy so that postulated support failure would have no consequence to overall system performance. Adequate redundancy is demonstrated if the adjacent supports are capable of sustaining the additional weight resulting from the postulated support failure.

5
DOCUMENTATION

A summary package should be assembled to document and track the Seismic Capability Engineers' evaluation activities. Documentation should include records of the HVAC duct and damper systems evaluated, the dates of the walkdowns, the names of the engineers conducting the evaluations, and a summary of results. Recommended data sheets for the summary package are given in Exhibits 5-1 to 5-5 and are described below.

Exhibit 5-1 provides a Screening and Evaluation Work Sheet (SEWS) that can be used to document the walkdowns. The SEWS includes reminders, as a checklist, for primary aspects of the evaluation guidelines; however, the walkdown engineers should be familiar with all aspects of the seismic evaluation guidelines during in-plant screening reviews and not rely solely on the checklist. The checklist items on the SEWS are worded so that all acceptable conditions are answered Y (for yes). Any condition that is answered N (for no) or U (for unknown) is an outlier. The SEWS should be signed and dated by at least two Seismic Capability Engineers, one of whom is a licensed professional engineer.

Exhibit 5-2 provides a Duct Support Analytical Review Data Sheet for recording information on the supports selected as the worst case, representative samples.

Exhibit 5-3 provides a Tracking Summary for the Duct Support Analytical Review Data Sheets. As items are completed and resolved, the responsible engineers should initial the line item on the tracking sheets to confirm final closure.

Exhibit 5-4 provides a HVAC Duct System Analytical Review Data Sheet for recording information on the duct system selected as worst case, representative samples for systems required to maintain pressure boundary.

Exhibit 5-5 provides a HVAC System Outlier Sheet (HSOS) for documenting outliers. An outlier is a HVAC duct system or support feature that does not meet the screening guidelines in Section 3, or a HVAC duct or support that does not meet the analytical review criteria in Section 4. The HSOS identifies the screening guidelines that are not met, the reasons for the outlier, and the proposed method of resolving the outlier. Outliers are discussed in Section 6.

Photographs may be used to supplement documentation as required. When used as formal documentation for the summary packages, photographs should be clearly labeled for identification.

Exhibit 5-1 Sheet 1 of ____

SCREENING AND EVALUATION WORK SHEET (SEWS)

HVAC System I.D. ____________________

Damper Equipment I.D. ____________________

System Description and Boundaries ____________________

____

____

HVAC System Locations and Reference Drawings ____________________

____

Duct Materials and Sizes ____________________

____

Linear Weight:

Duct		Insulation		Total	References
________	+	________	=	________	________
________	+	________	=	________	________
________	+	________	=	________	________

Concurrent Pressure and Temperature ____________________

<u>Applicability</u>

1. Operating temperature less than the temperature limitations in Table 2-1 — Y N U N/A
2. Plant ground spectrum enveloped by the SQUG Bounding Spectrum (Figure 2-1) and ZPA_h is less than 2.0g — Y N U N/A

Does duct meet applicability criteria? — Y N U

<u>Pressure Boundary Integrity Review</u>

1. Is pressure boundary integrity required? — Y N U N/A
   IF the answer to the above question is NO, SKIP THIS SECTION and proceed to the Structural Integrity Review
2. Stiffener spacings are within the guidelines — Y N U N/A
3. Bolted flanged joints satisfy SMACNA requirements — Y N U N/A
4. No point-supported round duct — Y N U N/A
5. Flexible bellows can accommodate motions — Y N U N/A
6. No additional concerns — Y N U N/A

Are the above caveats met? — Y N U

Exhibit 5-1 Sheet 2 of ____

SCREENING AND EVALUATION WORK SHEET (SEWS)

HVAC System I.D. ______________________________

Damper Equipment I.D. ______________________________

Structural Integrity Review

1. Support spans satisfy the criteria	Y	N	U	N/A
2. Ducts are properly tied-down to the supports	Y	N	U	N/A
3. Industry standard duct joints are utilized	Y	N	U	N/A
4. Slip joints can accommodate displacements	Y	N	U	N/A
5. Round duct joints exclude riveted lap joints	Y	N	U	N/A
6. Appurtenances are positively attached to duct	Y	N	U	N/A
7. Heavy in-line equipment is adequately restrained	Y	N	U	N/A
8. No stiff branch with flexible header	Y	N	U	N/A
9. Cantilevered duct section is attached to last support	Y	N	U	N/A
10. Ducts are free of corrosion detrimental to integrity	Y	N	U	N/A
11. System is free of obvious damage or defects	Y	N	U	N/A
12. No other concerns	Y	N	U	N/A
Are the above caveats met?	Y	N	U	

Support Review

1. Beam clamps are oriented to preclude slipping off the support	Y	N	U	N/A
2. Channel nuts have teeth or ridges	Y	N	U	N/A
3. No cast iron inserts	Y	N	U	N/A
4. No broken or obviously defective hardware	Y	N	U	N/A
5. Support is free of excessive corrosion	Y	N	U	N/A
6. Welded joints appear to be of good quality	Y	N	U	N/A
7. Anchorage appears adequate	Y	N	U	N/A
8. No stiff supports or hard spots in long flexible duct runs	Y	N	U	N/A
9. No short, fixed ended heavily loaded rod hangers subject to potential fatigue failure	Y	N	U	N/A
10. No additional concerns	Y	N	U	N/A
Are the above caveats met?	Y	N	U	

Damper Review

1. Damper is similar to and bounded by the seismic experience data for dampers in Attachment B	Y	N	U	N/A
2. Damper operator/actuator not of cast iron	Y	N	U	N/A
3. Attached lines have sufficient slack and flexibility	Y	N	U	N/A
4. Damper controls mounted separately from the damper adequately anchored	Y	N	U	N/A
5. Motor or pneumatic operator mounted on the damper has adequate anchorage and load path	Y	N	U	N/A
6. Duct at the damper location free from signs of distortion that could interfere with damper operation	Y	N	U	N/A
7. No other adverse concerns	Y	N	U	N/A
Are the above caveats met?	Y	N	U	

Exhibit 5-1 Sheet 3 of ____

SCREENING AND EVALUATION WORK SHEET (SEWS)

HVAC System I.D. ______________________________

Damper Equipment I.D. ______________________________

Seismic Interaction Review

1.	Free from impact by nearby equipment	Y	N	U	N/A
2.	No collapse of overhead equipment, distribution systems or masonry walls	Y	N	U	N/A
3.	Able to accommodate differential displacements	Y	N	U	N/A
4.	No other adverse concerns	Y	N	U	N/A

Are the above caveats met? Y N U

IS THE HVAC DUCT AND DAMPER SYSTEM SEISMICALLY ADEQUATE? Y N U

Supports Selected for Analytical Review ______________________________

Duct System Selected for Analytical Review ______________________________

Comments ______________________________

CERTIFICATION: (Signatures of at least two Seismic Capability Engineers are required; one of whom is a licensed professional engineer.)

Print or Type Name/Title	Signature	Date
Print or Type Name/Title	Signature	Date

Exhibit 5-2

DUCT SUPPORT ANALYTICAL REVIEW DATA SHEET

HVAC Duct System:______________________________ Selection No.:____________________________

Plant Location:___________________________________

Description and Sketch:

CERTIFICATION: (Signatures of at least two Seismic Capability Engineers are required; one of whom is a licensed professional engineer.)

Print or Type Name/Title	Signature	Date
______________________	______________________	______
______________________	______________________	______

Exhibit 5-3

Sheet 1 of ____

HVAC DUCT SUPPORT
ANALYTICAL REVIEW TRACKING SUMMARY

HVAC Duct System Designation	Plant Location	Selection Number	Final Resolution	Initials/ Date

Exhibit 5-4 Sheet 1 of ____

HVAC DUCT SYSTEM
ANALYTICAL REVIEW DATA SHEET

HVAC Duct System:______________________________ Selection No.:____________________________

Plant Location:__________________________________

Description and Sketch:

CERTIFICATION: (Signatures of at least two Seismic Capability Engineers are required; one of whom is a licensed professional engineer.)

______________________________	____________________________	______
Print or Type Name/Title	Signature	Date
______________________________	____________________________	______
Print or Type Name/Title	Signature	Date

Exhibit 5-5

Sheet 1 of ____

HVAC SYSTEM OUTLIER SHEET (HSOS)

OUTLIER NO. ________

1. OUTLIER IDENTIFICATION AND LOCATION

HVAC System I.D. ____

Location ____

____

2. OUTLIER ISSUE DEFINITION

a. Identify the screening guidelines that are not met, or indicate if the analytical review selection fails the analysis criteria.

Applicability	_____	Damper Review	_____
Pressure Boundary Integrity	_____	Interaction Effects	_____
Structural Integrity Review	_____	Support Analytical Review	_____
Support Review	_____	Duct Analytical Review	_____

b. Describe all the reasons for the outlier:

____

____

____

____

____

____

3. <u>PROPOSED</u> METHOD OF OUTLIER RESOLUTION (OPTIONAL)

a. Define the proposed method(s) for resolving the outlier:

____

____

____

b. Provide information needed to implement proposed method(s) for resolving the outlier:

____

____

____

CERTIFICATION: (Signatures of at least two Seismic Capability Engineers are required; one of whom is a licensed professional engineer.)

Print or Type Name/Title	Signature	Date
Print or Type Name/Title	Signature	Date

6 OUTLIERS

6.1 Identification of Outliers

An outlier is defined as a HVAC duct, damper or support feature that does not meet the screening guidelines in Section 3, or a HVAC duct or support selection that fails the analytical review criteria in Section 4. The guidelines and analysis criteria are intended to be used on a generic basis for seismic adequacy review of HVAC systems (including supports). HVAC duct, dampers or supports that do not pass the generic criteria may still be shown to be seismically adequate by obtaining additional information or by performing additional evaluations.

6.2 Outlier Resolution

An outlier may be shown to be adequate for seismic loadings by performing additional evaluations to demonstrate there is adequate seismic margin. These additional evaluations and alternate methods should be thoroughly documented to permit independent review. Methods to determine the available seismic margin are contained in EPRI NP-6041-SL [14].

In some cases it may be necessary to exercise engineering judgment when resolving outliers, since strict adherence to the screening guidelines is not absolutely required for HVAC systems to be seismically adequate. These judgments, however, should be based on a thorough understanding of the background and philosophy used to develop these screening guidelines as described in this report. The justification and reasoning for considering an outlier to be acceptable should be based on mechanistic principles and sound engineering judgment.

The screening guidelines contained in this report have been reviewed to ensure that they are appropriate for generic use; however, the alternative evaluation methods and engineering judgments used to resolve outliers are not subject to the same level of peer review. Therefore, the evaluations and judgments used to resolve outliers should be thoroughly documented so that independent reviews can be performed if necessary.

7 REFERENCES

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A
HVAC DUCT SYSTEM EARTHQUAKE EXPERIENCE DATA

A.1 Introduction

This attachment documents the performance history of HVAC duct and duct support systems under seismic loading. The bulk of data was obtained from extensive field investigations of systems that have experienced strong motion earthquakes. Further information on the performance of HVAC duct systems was gained from a literature search on earthquake damage in past earthquakes.

A summary of the known damage data for the performance of HVAC duct systems when subject to seismic loading is presented. The seismic experience database includes many examples of ducts that have performed well in actual earthquakes. The presented data focuses on examples of ducts that have performed poorly in seismic excitations, with a discussion of the attributes of the installations that caused them to perform poorly.

HVAC ducting is found at nearly all industrial sites. The seismic experience database therefore includes a vast amount of data on the survivability of ducting installed in many different ways, and experiencing many different seismic excitation levels. The large number of duct systems that have survived earthquakes indicate the inherent ruggedness of these systems. The limited, smaller set of HVAC duct systems that have been found to have performed poorly in a seismic event point out key characteristics of HVAC installations that may contribute to seismic damage.

A.2 Earthquake Experience Database

The seismic experience database is founded on studies of over 100 facilities located in the strong-motion areas of more than twenty strong-motion earthquakes that have occurred in the United States, Latin America, New Zealand, and other parts of the world since 1971 (see Table A-1).

The database was compiled through surveys of the following types of facilities:

- Fossil-fueled power plants
- Hydroelectric power plants
- Electrical distribution substations
- Oil processing and refining facilities

- Water treatment and pumping stations
- Natural gas processing and pumping stations
- Manufacturing facilities
- Large commercial facilities

In general, data collection efforts focused on facilities located in the areas of strongest ground motion for each earthquake investigated. Facilities were sought that contained substantial inventories of mechanical and electrical equipment or control and instrumentation systems. Because of the number of earthquake-affected areas and types of facilities investigated, there is a wide diversity in the types of installations included in the database. For the HVAC duct of focus in this study, there is a wide diversity in size, configuration, type of building, local soil conditions, and quality of construction.

The database currently includes in detail fourteen earthquakes from which duct data have been processed for this report. Each earthquake includes several different sites investigated within each epicentral area. The earthquakes investigated range in Richter magnitude (M) from 5.5 to 8.1. The strong motion duration is as high as forty seconds. Local soil conditions range from deep alluvium to rock.

The buildings housing the ductwork have a wide range in size and type of construction. As a result, the database covers a wide diversity of seismic input to duct installations, in terms of seismic motion, amplitude, duration, and frequency content.

Table A-1
Summary of Sites Reviewed in Compiling the Seismic Experience Database

Earthquake Magnitude	Facility	Type of Facility	Estimated Peak Ground Acceleration (g)**
San Fernando, CA Earthquake 1971 (M6.6)	Sylmar Station	Large electrical substation	0.65
	Rinaldi Receiving Station	Large electrical substation	0.50-0.75
	Valley Steam Plant	Four-unit gas-fired power plant	0.40
	Burbank Power Plant	Six-unit gas-fired power plant	0.25
	Glendale Power Plant	Five-unit gas-fired power plant	0.30
	Pasadena Power Plant	Five-unit gas-fired power plant	0.30
Point Mugu, CA Earthquake 1973 (M5.7)	Ormond Beach Power Plant	Large two-unit oil fired power plant	0.10
Ferndale CA Earthquake 1975 (M5.5)	Humboldt Bay Power Plant	Two gas-fired units, one nuclear unit	0.30*
Santa Barbara, CA Earthquake 1978 (M5.7)	Goleta Substation	Electrical substation	0.26*
Imperial Valley, CA Earthquake 1979 (M6.6)	El Centro Steam Plant	Four-unit gas-fired power plant	0.42*
	Drop IV Hydro. Plant	Two-unit hydroelectric	0.30
Humboldt, CA Earthquake1980 (M7.0)	Humboldt Bay Power Plant	Two gas-fired units one nuclear unit	0.25

* Ground acceleration measured by an instrument at the site
** Average of two horizontal components

Table A-1
Summary of Sites Reviewed in Compiling the Seismic Experience Database (continued)

Earthquake Magnitude	Facility	Type of Facility	Estimated Peak Ground Acceleration (g)**
Coalinga, CA Earthquake 1983 (M6.7)	Main Oil Pumping Plant	Pumping station feeding oil pipeline from Coalinga area	050
	Union Oil Butane Plant	Petrochemical facility to extract butane and propane from well waste gas	0.60
	Shell Water Treatment Plant	Petrochemical facility to demineralize water prior to steam injection into oil wells	0.60
	Coalinga Water Treatment Plant	Potable Water purification facility	0.52
	Coalinga Substation No. 2	Electrical substation	
	Shell Tank Farm No. 29	Oil storage	0.38
	Pleasant Valley Pumping Plant	Pumping station to supply water from the San Luis Canal to the Coalinga Canal	0.56*
	San Luis Canal Pumping Stations (29)	Agricultural pumping stations taking water from the San Luis Canal	0.20-0.60
	Gates Substation	Large electrical substation	0.25
	Kettleman Compressor Station	Natural gas pipeline booster station	0.20
Morgan Hill, CA Earthquake 1984 (M6.2)	United Tech Chemical Plant	Large research facility for missile systems development	0.50
	IBM/Santa Teresa Facility San Martin Winery	Large computer facility for software development Winery	0.37* 0.30
	Wiltron Electronics Plant	Electronics manufacturing facility	0.35
	Metcalf Substation	Large electrical substation	0.40

* Ground acceleration measured by an instrument at the site
** Average of two horizontal components

Table A-1
Summary of Sites Reviewed in Compiling the Seismic Experience Database (continued)

Earthquake Magnitude	Facility	Type of Facility	Estimated Peak Ground Acceleration (g)**
Morgan Hill, CA Earthquake 1984 (M6.2) (cont'd)	Evergreen Community College	Large college complex with self-contained HVAC power plant	0.20
	Mirassou Winery	Winery	0.20
Chile Earthquake 1985 (M7.8)	Bata Shoe Factory	Four-building factory and tannery	0.64
	San Isidro Substation	Electrical substation	0.58*
	Llolleo Water Pumping Plant	Water pumping station	0.78
	Terquim Tank Farm	Oil/acetate/acid storage tank farm	0.55
	Vicuna Hospital	Four-story hospital	0.55
	Rapel Hydroelectric Plant	Five-unit hydroelectric plant	0.40*
	San Sebastion Substation	Electrical substation	0.35
	Concon Petroleum Refinery	Petrochemical facility producing fuel oil, asphalt, gasoline and other petroleum products	0.30
	Oxiquim Chemical Plant	Chemical facility producing various chemicals, including feed stock for paint ingredients	0.30
	Concon Water Pumping Station	Water pumping station	0.30
	Renca Power Plant	Two-unit coal fired power plant	0.30
	Laguna Verde Power Plant	Two-unit coal-fired power plant	0.30
	Las Ventanas Copper Refinery	Copper refinery/foundry power plant	0.22

* Ground acceleration measured by an instrument at the site
** Average of two horizontal components

Table A-1
Summary of Sites Reviewed in Compiling the Seismic Experience Database (continued)

Earthquake Magnitude	Facility	Type of Facility	Estimated Peak Ground Acceleration (g)**
Chile Earthquake 1985 (M7.8) (cont'd)	Las Ventanas Power Plant	Two-unit coal-fired peaking plant	0.25
	San Cristobal Substation	Electrical substation	0.25
	Las Condes Hospital	Four-story hospital	0.20
Mexico Earthquake 1985 (M8.1)	La Villita Power Plant	Four-unit hydroelectric plant	0.14
	SICARTSA Steel Mill	Large modern steel mill	0.25-0.50
	Fertimex Fertilizer Plant	Fertilizer plant	0.25-0.50
Adak, Alaska Earthquake 1986 (M7.5)	Adak Naval Base	Diesel-electric power plants, electrical substations, sewage lift stations, water treatment plant, steam plants	0.25
North Palm Springs, CA Earthquake 1986 (M6.0)	Devers Substation	Large electrical distribution	0.85*
Chalfant Valley, CA Earthquake 1986 (M6.0)	Control Gorge Hydro Plant	Two-unit hydroelectric plant	0.25
San Salvador Earthquake 1986 (M5.4)	Soyopango Substation	Electrical substation	0.50
	San Antonio Substation	Electrical substation	0.40
Cerro Prieto, Mexico Earthquake 1987 (M5.4)	Power Plant 1	Geothermal power plant	0.20-0.30
	Power Plant 2	Geothermal power plant	0.20-0.30
Bay of Plenty, New Zealand Earthquake 1987 (M6.25)	Edgecumbe Substation	230/115kV substation	0.5-1.0

* Ground acceleration measured by an instrument at the site
** Average of two horizontal components

Table A-1
Summary of Sites Reviewed in Compiling the Seismic Experience Database (continued)

Earthquake Magnitude	Facility	Type of Facility	Estimated Peak Ground Acceleration (g)**
Bay of Plenty, New Zealand Earthquake 1987 (cont'd) (M6.25)	New Zealand Distillery	Liquor distillery	0.50-1.0
	Bay Milk	Dairy Products	0.50
	Caxton Paper Mill	Paper and pulp mill	0.40-0.55
	Kawerau Substation	230/115kV substation	0.40-0.55
	Whakatane Board Mill	Paper mill producing cardboard	0.25
	Matahina Dam	Two-unit hydro-electric plant	0.26*
Whittier, CA Earthquake 1987 (M5.9)	Olinda Substation	Electrical substation	0.65*
	SCE Central Dispatch Headquarters	Data Processing Center	0.56*
	SCE Headquarters	Large office complex	0.42*
	California Federal Bank Facility	Data processing facility	0.40
	Ticor Facility	Data processing facility	0.40
	Mesa Substation	Electrical substation	0.35
	Sanwa Bank Facility	Data processing facility	0.40
	Alhambra Telephone Station	Three-story concrete frame building	0.40
	Rosemead Telephone Station	Two-story steel-frame building	0.40
	Central Telephone Station	Three steel-frame high-rise buildings	0.15
	Wells Fargo Bank Facility	Data processing facility	0.30
	Center Substation	Electrical substation	0.26*
	Lighthype Substation	Electrical Substation	0.30

* Ground acceleration measured by an instrument at the site
** Average of two horizontal components

Table A-1
Summary of Sites Reviewed in Compiling the Seismic Experience Database (continued)

Earthquake Magnitude	Facility	Type of Facility	Estimated Peak Ground Acceleration (g)**
Whittier, CA Earthquake 1987 (M5.9) (cont'd)	Del Amo Substation	Electrical Substation	0.20
	Pasadena Power Plant	Five-unit gas-fired power plant	0.20
	Glendale Power Plant	Five-unit gas-fired power plant	0.25
	Commerce Refuse-to-Energy Plant	One-unit gas-fired power plant	0.40
	Puente Hills Landfill Gas and Energy Recovery Plant	One-unit gas-fired power plant	0.20
Superstition Hills El Centro, CA 1987 (M6.3)	Mesquite Lake Resource Recovery Plant	16 MW gas-fired power plant	0.20
	El Centro Steam Plant	Four-unit gas-fired power plant	0.25*
Loma Prieta Earthquake 1989 (M7.1)	Moss Landing Power Plant	Seven-unit gas-fired power plant	0.34
	Gilroy Energy Cogen Plant	One-unit combined gas turbine and steam turbine plant	0.40
	Cardinal Cogen Plant	One-unit combined gas turbine and steam turbine plant	0.25
	UCSC Cogen Plant	One-unit diesel cogeneration plant	0.44
	Hunter's Point Plant	Three-unit gas-fired power plant	0.15
	Protrero Plant	One-unit gas fired plant	0.15
	Metcalf Substation	500 kV substation	0.30
	San Mateo Substation	230 kV substation	0.20

* Ground acceleration measured by an instrument at the site
** Average of two horizontal components

Table A-1
Summary of Sites Reviewed in Compiling the Seismic Experience Database (continued)

Earthquake Magnitude	Facility	Type of Facility	Estimated Peak Ground Acceleration (g)**
Loma Prieta Earthquake 1989 (M7.1) (cont'd)	National Refractory	Large brick & magnesia extraction plant	0.30
	Green Giant Foods	Concrete tilt-up food processing plant	0.33
	Watson Wastewater Treatment	Sewage treatment plant	0.40
	Santa Cruz Telephone Station	Three-story concrete shear wall switching station	0.50
	Watsonville Telephone Station	Four-story concrete shear wall switching station	0.33*
	Seagate Technology Watsonville	Concrete tilt-up manufacturing facility	0.40
	Santa Cruz Water Treatment	Potable water purification facility	0.42
	Soquel Water District Headquarters	One-story wood-frame office complex with small pumping station & storage tanks	0.50
	Lipton Foods	Concrete tilt-up food processing and packaging facility	0.30
	Lone Star Cement	Large cement factory	0.25
	Watkins-Johnson Instruments	One-, two-, and three-story concrete & steel-frame buildings for light manufacturing	045
	Riconada Water Treatment Plant	Potable water processing facility	0.30
	IBM/Santa Teresa Facility	Steel-frame high-rise complex for software development	0.20

* Ground acceleration measured by an instrument at the site
** Average of two horizontal components

Table A-1
Summary of Sites Reviewed in Compiling the Seismic Experience Database (continued)

Earthquake Magnitude	Facility	Type of Facility	Estimated Peak Ground Acceleration (g)**
Loma Prieta Earthquake 1989 (M7.1) (cont'd)	EPRI Headquarters	Two-and three-story concrete-frame office	0.25
	San Martin Winery	Winery	0.30
Central Luzon Phillipines Earthquake 1990 (M7.7)	Baguio Telephone	Telephone switching station	--
	Cabanatuan Substation	230 kV substation	--
	La Trinidad Substation	230 kV substation	--
	San Manuel Substation	230 kV substation	--
	Moog Manufacturing Plant	Manufacturing plant	--
Valle de Estrella, Costa Rica Earthquake 1991 (M7.4)	Bomba Water Treatment Plant	Water treatment plant	--
	Cachi Dam	1,000 MW hydroelectric plant	0.12*
	Changuinola Power Plant	Diesel power plant	--
	Limon Telephone	Telephone switching station	--
	Moin Power Plant	140 MW thermoelectric power plant	--
	RECOPE Refinery	Oil refinery	
Sierra Madre, California Earthquake 1991 (M5.8)	Pasadena Power Plant	Five-unit gas-fired power plant	0.20
	Goodrich Substation	230 kV substation	0.30
Cape Mendocino, California Earthquake 1992 (M7.0)	PALCO Co-generation Plant	Two-unit power plant	0.47

*Ground acceleration measured by an instrument at the site
** Average of two horizontal components

Table A-1
Summary of Sites Reviewed in Compiling the Seismic Experience Database (continued)

Earthquake Magnitude	Facility	Type of Facility	Estimated Peak Ground Acceleration (g)**
Cape Mendocino, California Earthquake 1992 (M7.0) (cont'd)	Humboldt Bay Power Plant	Two gas-fired units, one nuclear unit	0.24
	Centerville Beach Station	Naval facility	0.40*
Landers and Big Bear, California Earthquake 1992 (M 7.6)	Cool Water Generation Plant	Four-unit power plant, two gas/oil-fired and two combined cycle units	0.36*
	Mitsubishi Cement Plant	Cement plant	--
	LUZ Projects	Solar electric generating station	0.35
Northridge, California Earthquake 1994 (M 6.7)	AES Placerita Cogeneration Plant	Two-unit electric gas turbine generators (80MW), two heat recovery steam generators and one 20 MW steam turbine generator	0.60
	ARCO Placerita Cogeneration Plant	Two-unit electric gas turbine generators and two heat recovery steam generators	0.60
	Pitchess Cogeneration Plant	21 MW electric gas turbine and heat recovery steam generator	0.50
	Olive View Cogeneration Plant	6MW power generation and heat recovery system	0.72
	Valley Steam Plant	Four-unit gas-fired power plant	0.40
	Burbank Power Plant	Six-unit gas-fired power plant	0.30
	Glendale Power Plant	Five-unit gas-fired power plant (148MW)	0.25

* Ground acceleration measured by an instrument at the site
** Average of two horizontal components

A.2.1 Facilities Surveyed in Compiling the Database

Information on each database facility, its performance during the earthquake, and any damage or adverse effects caused by the earthquake were collected through the following sources:

- Interviews with the facility management and operating personnel usually provide the most reliable and detailed information on the effects of the earthquake on each facility. At most facilities, several individuals were consulted to confirm or enhance details. In most cases, interviews are recorded on audio tape.
- Observations by earthquake reconnaissance teams are documented and photographed. Typical observations include descriptions and details of both damaged and undamaged installations or equipment and any indications of the cause of damage, such as substantial ground settlement or evidence of seismic interaction.
- The facility operating logs provide a written record of the conditions of the operating systems before and after the earthquake. Operating logs list problems in system operation associated with the earthquake and usually tabulate earthquake damage to the facility. Operating logs are useful in determining how long the facility may have been out of operation following the earthquake and any problems encountered in restarting the facility.
- The facility management often produces a report summarizing the effects of the earthquake following detailed inspections. These reports normally describe causes of any system malfunctions or damage.
- Earthquake damage can often be inspected prior to repairs if the facility can be surveyed immediately following the earthquake. This has been the case in most of the earthquakes included in the database.

Standard procedures used in surveying database facilities focus on collecting all information on damage or adverse effects of any kind caused by the earthquake. Seismic damage to well-engineered facilities is normally limited to only a few items except at sites that experience very high seismic motion, that is, in excess of 0.50g Peak Ground Acceleration (PGA), or greater than thirty seconds of strong motion.

Information on damaged and undamaged ductwork consists of photographs, measurements made at the site, visual observations, qualitative assessments of details and workmanship, and information supplied by personnel at the individual sites. This information includes typical assemblies, unusual details or systems, and supports that appear to be especially weak and prone to damage or failure.

An extensive search of the seismic experience database revealed *thirty-nine* sites in *fourteen* different earthquakes where ducting experienced PGAs of at least 0.25g. *Eighteen* of the *thirty-nine* experienced 0.40g or greater. The database sites represented a wide variety of duct sizes, shapes, configurations and support types. Round and rectangular ducts were found at seventeen and thirty-five sites, respectively, with sizes ranging from six to seventy-two inches. The above data have been compiled and summarized according to database site, duct construction type and size, support type, building type, and noted damage. This information is shown in Table A-2.

Table A-2
HVAC Duct Seismic Experience Database

		Duct Type				Support Type			Damage			Building Type		
Site	**PGA**	**Round**	**Rect-angle**	**Duct Size**	**Rod Hung**	**Strap**	**Canti-Lever**	**Frame**	**Falling**	**Dented**	**Concrete Block/ Shearwall**	**Tilt-Up**	**Frame**	**Framed Shearwall**
ADAK	0.25	X		10" 0							X			
ADAK	0.25	X	X	10" 0	X	X					X			
ADAK	0.25		X	12 X 12		X								X
ADAK	0.25		X	12 X 12	X									X
ADAK	0.25	X			X									X
ADAK	0.25		X	12 X 12		X							X	
ADAK	0.25	X		~24" 0							X			
BATA SHOE FACTORY	0.64		X	12 X 12										X
BATA SHOE FACTORY	0.64		X	36 X 24										X
BAY MILK	0.50		X	24 X 24							X			
BAY MILK	0.50		X	VERT. RUN	CABLE									
BURBANK	0.30	X		15"0				X						
BURBANK	0.30		X	LARGE	NV									
BURBANK POWER	0.30		X	LARGE										
BURBANK POWER	0.30		X	LARGE										
BURBANK POWER	0.30		X	LARGE										
CAL FED	0.40		X	60 X 48				X			X			
CAL FED	0.40		X	30 X 8		X					X			
CAL FED	0.40		X	30 X 8		X					X			
CAL FED	0.40		X	30 X 8		X					X			

Legend:

NV	Not Visible	FR	Framed
CSW	Concrete Shear Wall	BR	Braced
RC	Reinforced Concrete	NA	Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	**PGA**	**Round**	**Rect-angle**	**Duct Size**	**Rod Hung**	**Strap**	**Canti-Lever**	**Frame**	**Falling**	**Dented**	**Concrete Block/ Shearwall**	**Tilt-Up**	**Frame**	**Framed Shearwall**
CAXTON	0.40		X	16 X 16	NV	NV	NV	NV						
CAXTON	0.40		X	18 X12	NV	NV	NV	NV						FR/CBW
CAXTON	0.40	X		8" 0	ROPE									FR/CBW
CAXTON	0.40		NV	8' 0	NV	NV	NV	NV						FR/CBW
CAXTON	0.40		X	NV	X									FR/CBW
CAXTON	0.40	X		FLEX DUCT									X	
CAXTON	0.40		X	18 X 18	X									
CAXTON	0.40	X		18" 0						SPLIT				FR/CBW
CAXTON	0.40	X		18"0						SPLIT				FR./CBW
CAXTON	0.40	X		18"0		BEAM CLAMP								FR/CBW
CAXTON	0.40	X		18"0		BEAM CLAMP								FR/CBW
CAXTON	0.40	X		18"0		BEAM CLAMP								FR/CBW
CAXTON	0.40	X		18"0		BEAM CLAMP								FR-CBW
CAXTON	0.40		X	18 X18	X									FR/CBW
CAXTON	0.40		X	18'X8	X		PROPPED							RC
CAXTON	0.40		X	30 X 30										X
CAXTON	0.40		X	18 X 18			PROPPED						X	
CAXTON	0.40		X	18 X 18			PROPPED						X	
CAXTON	0.40		X	NV										X
CAXTON	0.40		X		NV									
CAXTON	0.40		X	18 X 18	X									X
CAXTON	0.40		X		X									
CAXTON	0.40		X	NV	NV						CSW			
CAXTON	0.40		X		X						CSW			
CAXTON	0.40	X		12" 0						X				
CAXTON	0.40	X		NV						X				
CAXTON	0.40	X		NV										

Legend: NV Not Visible — FR Framed
CSW Concrete Shear Wall — BR Braced
RC Reinforced Concrete — NA Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	**PGA**	**Round**	**Rect-angle**	**Duct Size**	**Rod Hung**	**Strap**	**Canti-Lever**	**Frame**	**Falling**	**Dented**	**Concrete Block/ Shearwall**	**Tilt-Up**	**Frame**	**Framed Shearwall**
COMMERCE	0.40	X		24"0				X					X	
COMMERCE	0.40	X	X	24",12X12				X					X	
COMMERCE	0.40	X	X	12"0 24x24									X	
COMMERCE	0.40	X		20"0	X								BRACED	
COMMERCE	0.40	X		20"0	X								BRACED	
COMMERCE	0.40	X		16"0 24"0	X								BRACED	
COMMERCE	0.40		X	60 X 60				X					X	
COMMERCE	0.40	X	X	24"030X30	X								X	
COMMERCE	0.40	X		24"0	X								X	
CONCON PETROLEUM	0.30		X	18 X 12			PROPPED						X	
DEVERS	0.85		X	NV							X			
DEVERS	0.85		X	NV	-	-	-	-						
DROP IV	0.30		X	18" X 24"				LIGHT			CSW			
DROP IV	0.30		X	24" X 48"				LIGHT			CSW			
DROP IV	0.30		X	VARIOUS				LIGHT			CSW			
EL CENTRO	.42, .25		X	36 X 36				X						X
EL CENTRO	.42, .25		X		X									X
EL CENTRO	.42, .25		X	60"X24"	X									X
EL CENTRO	.42, .25		X	24"X24"				ANGLE LEGS						
EL CENTRO	.42, .25		X	24"X24"				ANGLE LEGS						
EL CENTRO	.42, .25		X	36"X72"	X								X	
EL CENTRO	.42, .25		X	36"X72"	X								X	

Legend:
NV Not Visible
CSW Concrete Shear Wall
RC Reinforced Concrete
FR Framed
BR Braced
NA Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	PGA	Round	Rect-angle	Duct Size	Rod Hung	Strap	Canti-Lever	Frame	Falling	Dented	Concrete Block/ Shearwall	Tilt-Up	Frame	Framed Shearwall
EL CENTRO	.42, .25		X	V. 42"X42"				X						
EL CENTRO	.42, .25		X	VARIES				ANGLE LEGS						
EL CENTRO	.42, .25		X	VARIES				ANGLE LEGS						
EL CENTRO	.42, .25		X					X						
EL CENTRO	.42, .25		X	60 X 80				X						
EL CENTRO	.42, .25		X	48 X 30				X						
EL CENTRO	.42, .25		X	36 X 98				X						
EL CENTRO	.42, .25		X	NV				X					X	
EL CENTRO	.42, .25		X	NV	X									
EL CENTRO	.42, .25		X											
EL CENTRO	.42, .25		X	NV										
EL CENTRO	.42, .25		X	NV				POSTS						
EL CENTRO	.42, .25	X		20" 0										X
EL CENTRO	.42, .25		X	60" X 20"	X									X
EL CENTRO	.42, .25		X	28" X 12"				X						
EL CENTRO	.42, .25		X	24" X 60"				X						
EL CENTRO	.42, .25		X	24" X 60"				X						

Legend:
NV Not Visible; FR Framed
CSW Concrete Shear Wall; BR Braced
RC Reinforced Concrete; NA Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	**PGA**	**Round**	**Rect-angle**	**Duct Size**	**Rod Hung**	**Strap**	**Canti-Lever**	**Frame**	**Falling**	**Dented**	**Concrete Block/ Shearwall**	**Tilt-Up**	**Frame**	**Framed Shearwall**
EL CENTRO	.42, .25		X		X			X					X	
EL CENTRO	.42, .25		X	48" X 24"	X									
EL CENTRO	.42, .25			48" X 24"	X									
EL CENTRO	.42, .25		X	54 X 54										X
EL CENTRO	.42, .25		X	VAR. 48X48				X			-	NA	-	-
EL CENTRO	.42, .25		X	NV							NA	NA	NA	NA
EL CENTRO	.42, .25		X	NV							NA	NA	NA	NA
EL CENTRO	.42, .25		X	48 X 24										X
EL CENTRO	.42, .25		X	NV				X						X
EL CENTRO	.42, .25		X		NV									
EL CENTRO	.42, .25		X					X						
EL CENTRO	.42, .25		X	LARGE				X						
EL CENTRO	.42, .25		X	36 X 120			PROPPED							
EL CENTRO	.42, .25		X				PROPPED							
EL CENTRO	.42, .25		X	NV										
EL CENTRO	.42, .25		X	48 X 24				X						X
EL CENTRO STEAM	.42, .25		X	24 X 24				X						

Legend:
NV Not Visible
CSW Concrete Shear Wall
RC Reinforced Concrete
FR Framed
BR Braced
NA Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	**PGA**	**Round**	**Rect-angle**	**Duct Size**	**Rod Hung**	**Strap**	**Canti-Lever**	**Frame**	**Falling**	**Dented**	**Concrete Block/ Shearwall**	**Tilt-Up**	**Frame**	**Framed Shearwall**
EL CENTRO STEAM	.42, .25		X	24 X 30										
EL CENTRO STEAM	.42, .25		X		X									
EL CENTRO STEAM	.42, .25		X	24 X 18										X
FERTIMEX	0.25-0.5		X	24 X 24	X								X	
FERTIMEX	0.25-0.5		X	24 X 30	X				X				X	
FERTIMEX	0.25 0.5		X	12 X 16	X								X	
FERTIMEX	0.25-0.5		X	24 X 24	X								X	
FERTIMEX	0.25-0.5		X	24 X 24	X								X	
FERTIMEX	0.25-0.5		X	60 X 30									X	
FERTIMEX	0.25-0.5		X	12 X 18	X								X	
FERTIMEX	0.25-0.5		X	30 X 18	X								X	
FERTIMEX	0.25-0.5		X	24 X 12	X								X	
FERTIMEX	0.25-0.5		X	16 X 16	X								X	
FERTIMEX	0.25-0.5		X	72 X 72				X			NA	NA	NA	NA
FERTIMEX	0.25-0.5		X	24 X 12	X								X	
FERTIMEX	0.25-0.5		X	NV	NV	NV	NV	NV					X	
FERTIMEX	0.25-0.5		X	24 X 24	NV	NV	NV	NV					X	

Legend:

NV	Not Visible	FR	Framed
CSW	Concrete Shear Wall	BR	Braced
RC	Reinforced Concrete	NA	Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	**PGA**	**Round**	**Rect-angle**	**Duct Size**	**Rod Hung**	**Strap**	**Canti-Lever**	**Frame**	**Falling**	**Dented**	**Concrete Block/ Shearwall**	**Tilt-Up**	**Frame**	**Framed Shearwall**
GILROY COGEN	0.40		X	24 X 48				X			NA	NA	NA	NA
GILROY COGEN	0.40		X	18 X 12	NONE	NONE	NONE	NONE			CSW			
GLENDALE POWER	0.30		X	LARGE										
GLENDALE POWER	0.30		X	LARGE										
GLENDALE POWER	0.30		X	LARGE										
GLENDALE POWER	0.30		X	LARGE				X						
GLENDALE POWER	0.30		X	LARGE										
GLENDALE POWER	0.30		X	30 X 30				X						
GLENDALE POWER	0.30	X		NV	X									
GLENDALE POWER	0.30		X	LARGE										
GLENDALE POWER	0.30		X	24 X 24	NV									
GLENDALE POWER	0.30		X	36 X 18	NV									X
GLENDALE POWER	0.30		NV	NV	NV									NV
GLENDALE POWER	0.30		X	18 X 6	X									X
GLENDALE POWER	0.30		X	18 X 30			PROPPED							X
GLENDALE POWER	0.30		X	NV	X									
GLENDALE POWER	0.30	X	X	25"0										

Legend:
NV Not Visible
CSW Concrete Shear Wall
RC Reinforced Concrete
FR Framed
BR Braced
NA Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	**PGA**	**Round**	**Rect-angle**	**Duct Size**	**Rod Hung**	**Strap**	**Canti-Lever**	**Frame**	**Falling**	**Dented**	**Concrete Block/ Shearwall**	**Tilt-Up**	**Frame**	**Framed Shearwall**
GLENDALE POWER	0.30		X	18 X 30			PROPPED							
GLENDALE POWER	0.30		X	NV										
GLENDALE POWER	0.30	X		NV		X								
GLENDALE POWER	0.30		X	30 X 18		X								
GLENDALE POWER	0.30		X	24 X 18	X									
GLENDALE POWER	0.30		X	18 X 6	X									
GLENDALE POWER	0.30		X	30 X 18		X								
GLENDALE POWER	0.30		X	NV				X					X	
HUMBOLDT	.25, .30	X		36"0				X						
HUMBOLDT BAY	.25, .30		X	NV				X						
HUMBOLDT BAY	.25, .30		X	NV				X						
HUMBOLDT BAY	.25, .30	X		NV										
HUMBOLDT BAY	.25, .30		X	LARGE				X					X	
HUMBOLDT BAY	.25, .30		X	12 X 12				X					X	
HUMBOLDT BAY	.25, .30		X	-				X	NV	NV			X	
HUMBOLDT BAY	.25, .30		X	NV									X	
HUMBOLDT BAY	.25, .30		X	NV										

Legend:

NV	Not Visible	FR	Framed
CSW	Concrete Shear Wall	BR	Braced
RC	Reinforced Concrete	NA	Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	**PGA**	**Round**	**Rect-angle**	**Duct Size**	**Rod Hung**	**Strap**	**Canti-Lever**	**Frame**	**Falling**	**Dented**	**Concrete Block/ Shearwall**	**Tilt-Up**	**Frame**	**Framed Shearwall**
HUMBOLDT BAY	.25, .30	X		18"0				X						
HUMBOLDT BAY	.25, .30		X	VARIES				X						
HUMBOLDT BAY	.25, .30		X	NV	X						CSW			
HUMBOLDT BAY	.25, .30	X		30"0				X						
HUMBOLDT BAY	.25, .30		X	NV										
HUMBOLDT BAY	.25, .30	X	X	18" 0										
HUMBOLDT BAY	.25, .30		X	NV										
HUMBOLDT BAY	.25, .30	X		18" 0				X						
HUMBOLDT BAY	.25, .30	X		16" 0				X						
IBM SANTA TERESA	0.37		X	24 X 12	X								X	
IBM SANTA TERESA	0.37		X	24 X 12	X								X	
KETTLEMAN	0.20	X		16" 0										
LA VILLITA	0.14		X	NV									X	
LA VILLITA	.14		X	18 X 18			X						X	
HUMBOLDT BAY	.25, .30	X												
HUMBOLDT BAY	.25, .30		X	24 X 18				X					X	
HUMBOLDT BAY	.25, .30			24 X 18				X						
HUMBOLDT BAY	.25, .30	X	X	LARGE				X					X	

Legend:

NV	Not Visible	FR	Framed
CSW	Concrete Shear Wall	BR	Braced
RC	Reinforced Concrete	NA	Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	**PGA**	**Round**	**Rect-angle**	**Duct Size**	**Rod Hung**	**Strap**	**Canti-Lever**	**Frame**	**Falling**	**Dented**	**Concrete Block/ Shearwall**	**Tilt-Up**	**Frame**	**Framed Shearwall**
HUMBOLDT BAY	.25, .30		X					X						
IBM SANTA TERESA	0.37		X	24XVARIES	X								X	
IBM SANTA TERESA	0.37		X	24 X 12	X								X	
IBM SANTA TERESA	0.37		X	24 X 12	X								X	
LAS VENTANAS	0.22	X	X	36 X 36				X					X	
LAS VENTANAS	0.22		X	18 X18	X						CSW			
LAS VENTANAS COP.	0.22	X		120" 0				X					X	
MEQUITE LAKE	0.20	X		24"0,36"0				X					X	
MESQUITE LAKE	0.20		X	24 X 24										
MESQUITE LAKE	0.20	X		24" 0				X					X	
MESQUITE LAKE	0.20	X		24" 0				X			NA	NA	NA	NA
MESQUITE LAKE	0.20		X	36 X 36							NA	NA	NA	NA
MESQUITE LAKE	0.20	X		LARGE				X						
MESQUITE LAKE	0.20	X		NV				X					X	
MESQUITE LAKE	0.20		X	18 X 18				X					X	
MESQUITE LAKE	0.20	X		60" 0				X					X	

Legend:
NV Not Visible
CSW Concrete Shear Wall
RC Reinforced Concrete
FR Framed
BR Braced
NA Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	**PGA**	**Round**	**Rect-angle**	**Duct Size**	**Rod Hung**	**Strap**	**Canti-Lever**	**Frame**	**Falling**	**Dented**	**Concrete Block/ Shearwall**	**Tilt-Up**	**Frame**	**Framed Shearwall**
MT. UMANUM	0.50		X	VARIES	X	X					CSW			
MT. UMANUM	0.50		X	24 X 16	X	X					CSW			
MT. UMANUM	0.50		X	24 X 16	X	X					CSW			
MT. UMANUM	0.50		X	16 X 12	X	X					CSW			
MT. UMANUM	0.50		X	16 X 18	X	X					CSW			
PAC BELL WATSON-VILLE	0.33		X	12 X 6							CSW			
MT. UMANUM	0.50		X	16 X 18	X	X					CSW			
MT. UMANUM	0.50		X	16 X 18	X	X					CSW			
MT. UMANUM	0.50		X	16 X 16		X					CSW			
MT. UMANUM	0.50		X	16 X 16		X					CSW			
ORMOND BEACH	0.10		X	18 X 18	X									
PAC BELL ALHAMBRA	0.40		X	12 X 20						X				X
PAC BELL WATS.	0.33		X	24 X 8	X									
PAC BELL WATSONVILLE	0.33		X	12 X 6	X						CSW			
PAC BELL WATSONVILLE	0.33		X	24 X 8							CSW			
PAC BELL WATSONVILLE	0.33		X	16 X 8							CSW			

Legend: NV Not Visible; CSW Concrete Shear Wall; RC Reinforced Concrete; FR Framed; BR Braced; NA Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	**PGA**	**Round**	**Rect-angle**	**Duct Size**	**Rod Hung**	**Strap**	**Canti-Lever**	**Frame**	**Falling**	**Dented**	**Concrete Block/ Shearwall**	**Tilt-Up**	**Frame**	**Framed Shearwall**
PAC BELL WATSONVILLE	0.33		X	NV					X		CSW			
PAC BELL WATSONVILLE	0.33		X						X		CSW			
PUENTE HILLS	0.20		X	NV				LEGS			NA	NA	NA	NA
RENCA	0.30		X					X					X	
RINALDI	0.50		X	NV										
SAN MARTIN	.30, .30		X	NV						X				
SAN MARTIN	.30, .30		X	NV	X					X				
SANWA	0.40		X	30 X 18	NV	NV	NV	NV						X
SANWA BANK	0.40		X			X				X				X
SCE ROSEMEAD	0.42		X	24 X 24							CSW			
SCE ROSEMEAD	0.42		X	30 X 15		X				X	CSW			
SEAGATE	0.40	X		18"0		X						X		
SEAGATE	0.40	X		12"0 16"0		X			X			X		
SEAGATE	0.40	X		12"0 16"0		X			X			X		
SEAGATE	0.40	X		16"0								X		
SEAGATE	0.40	X		24" 0								X		
SEAGATE	0.40	X		24"0		X						X		

Legend:

NV	Not Visible	FR	Framed
CSW	Concrete Shear Wall	BR	Braced
RC	Reinforced Concrete	NA	Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	PGA	Round	Rect-angle	Duct Size	Rod Hung	Strap	Canti-Lever	Frame	Falling	Dented	Concrete Block/ Shearwall	Tilt-Up	Frame	Framed Shearwall
SICARTSA	0.25		X	NV		X							X	X
SICARTSA	0.25		X	NV		X							X	
SICARTSA	0.25		X	42 X 42									X	
SICARTSA	0.25		X	12 X 12	NV	NV	NV	NV					X	
SICARTSA	0.25		X	NV		X							X	
SYLMAR	0.65		X	12 X 8										
SYLMAR	0.65		X	18 X 6		X							BR STEEL	
SYLMAR	0.65		X	24 X 18	X								BR STEEL	
SYLMAR	0.65	X	X	28 X 18	NV								BR STEEL	
SYLMAR	0.65	X	X	18 0	NV								BR STEEL	
SYLMAR	0.65		X	24 X 18		X							BR STEEL	
SYLMAR	0.65		X	VARIES	NV								BR STEEL	
SYLMAR	0.65		X	VARIES	X								BR STEEL	
SYLMAR	0.65		X	24 X 24	X								BR STEEL	
SYLMAR	0.65		X	12 X 6		X							BR STEEL	
SYLMAR	0.65		X	36 X 18	NV								BR STEEL	
SYLMAR	0.65		X	24 X 12	X								BR. STEEL	
SYLMAR	0.65		X	20 X10	X								BR STEEL	

Legend: NV Not Visible FR Framed
CSW Concrete Shear Wall BR Braced
RC Reinforced Concrete NA Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	PGA	Round	Rect-angle	Duct Size	Rod Hung	Strap	Canti-Lever	Frame	Falling	Dented	Concrete Block/ Shearwall	Tilt-Up	Frame	Framed Shearwall
SYLMAR	0.65		X	VARIES									BR STEEL	
SYLMAR	0.65		X	60 X 18	X								BR STEEL	
SYLMAR	065		X	18 X 12	X								BR STEEL	
SYLMAR	065		X	~30 X 12	X								BR STEEL	
SYLMAR	065		X	20 X 8									BR STEEL	
SYLMAR	065		X	12 X 12	X								BR STEEL	
UCSC COGEN	0.44	X		20"0		CABLES								FR/CBW
UNION OIL	0.60		X	LARGE										
UNION OIL	0.60		X	LARGE				X					X	
VALLEY STEAM	0.40		X	36 X 36										
VALLEY STEAM	0.40		X	LARGE				X						
VALLEY STEAM	0.40		X	18 X 6		X								
VALLEY STEAM	0.40		X	NV				X						
VALLEY STEAM	0.40		X	NV	SPRINGS								X	
VALLEY STEAM	0.40		X	NV	SPRINGS								X	
VALLEY STEAM	0.40	X		14" 0										
VALLEY STEAM	0.40		X	LARGE				X						

Legend: NV Not Visible — FR Framed
CSW Concrete Shear Wall — BR Braced
RC Reinforced Concrete — NA Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	PGA	Round	Rect-angle	Duct Size	Rod Hung	Strap	Canti-Lever	Frame	Falling	Dented	Concrete Block/ Shearwall	Tilt-Up	Frame	Framed Shearwall
WATKIN JOHNSON	0.45		X	30 X 30				UNISTRUT						X
WATKINS-JOHNSON	0.45	X		36"0,12"0	CABLES									X
WATKINS JOHNSON	0.45	X		6"0	X								X	
WATKINS JOHNSON	0.45		X	30 X 30				UNISTRUT						X
WATKINS JOHNSON	0.45		X	18 X 18				UNISTRUT						X
WATKINS JOHNSON	0.45		X	NV				UNIST. ANC						
WATKINS JOHNSON	0.45		X	48 X 24				X						
WATKINS JOHNSON	0.45		X	NV	NV									
WATKINS JOHNSON	0.45		X	NV	NV	NV	NV	NV						X
WATKINS-JOHNSON	0.45			18 X 18				UNISTRUT						
WATS PAC BELL	0.33		X	NV										X
WATS PAC BELL	0.33		X	18 X 8'		X								X
WATS. PAC BELL	0.33		X	12" X 12"		X					CSW			
WATS. PAC BELL	0.33		X	18 X 6	X									X
WATS. PAC BELL	0.33		X	24 X 8'	X									X

Legend:
NV Not Visible
CSW Concrete Shear Wall
RC Reinforced Concrete
FR Framed
BR Braced
NA Not Applicable

Table A-2
HVAC Duct Seismic Experience Database (continued)

		Duct Type				Support Type			Damage			Building Type		
Site	PGA	Round	Rect-angle	Duct Size	Rod Hung	Strap	Canti-Lever	Frame	Falling	Dented	Concrete Block/ Shearwall	Tilt-Up	Frame	Framed Shearwall
WATS. WASTE WATER	0.40		X	30 X 16	X								X	
WHAKATANE	0.25		X	18 X 10	X								RC	
WHAKATANE	0.25	X			X								RC	
WHAKATANE	0.25		X	24 X 10	X								RC	
WHAKATANE	0.25		X	24 X 12	X								RC	
WHAKATANE	0.25		X	20 X 12	X								RC	
WHAKATANE	0.25	X		16" 0	NV						X			
WILTRON	0.35	X		12" 0		X			X	X		X		
WILTRON	0.35	X		12" 0		X			X	X		X		
WILTRON	0.35	X		12" 0		X			X	X		X		
WILTRON	0.35	X	X	12" 0		X			X	X		X		
WILTRON	0.35	X		12" 0		X			X	X		X		

Legend:
NV Not Visible; FR Framed
CSW Concrete Shear Wall; BR Braced
RC Reinforced Concrete; NA Not Applicable

The large number of duct systems that have survived earthquakes indicates the inherent ruggedness of these systems. The light gauge sheet metal ducts were constructed with pocket locks, companion angles, and riveted connections. In many cases the ducting had no stiffener angles and still survived the strong motion. Generally, the database HVAC ducts were supported with either rod hangers or long sheet metal straps; however, there were also instances of frame-mounted ducts. Some HVAC ducts were hung with rope, cables, or wire. Rod hanger supports were typically trapezes which were attached to concrete ceilings with expansion anchors, or either clamped or threaded and tapped into overhead steel structures. Sheet metal strap supports were usually spot welded to the duct sides and attached to overhead ceilings with expansion anchors. Figures A-1 through A-12 illustrate some of the typical database duct configurations and supports that have survived past strong-motion earthquakes.

Figure A-1
Sylmar Converter Station, 1971 San Fernando Earthquake. Strap-Hung and Wall-Mounted Duct With Wall Penetrations

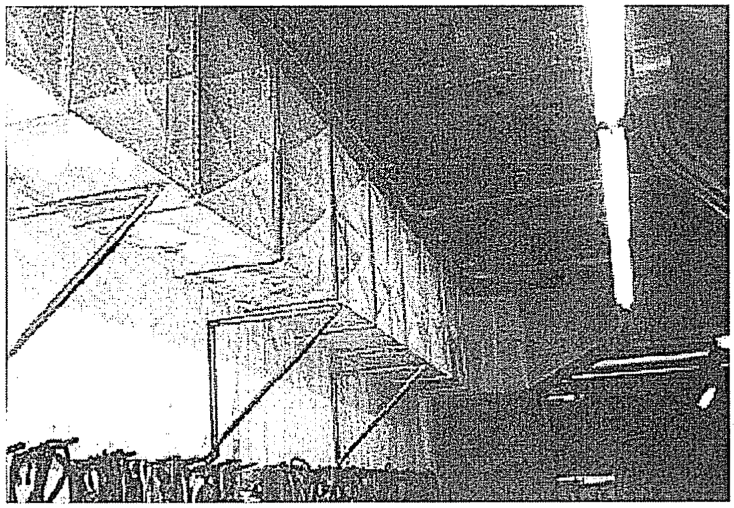


Figure A-2
Glendale Power Plant, 1971 San Fernando Earthquake. Cantilever Bracket Supported Rectangular Duct

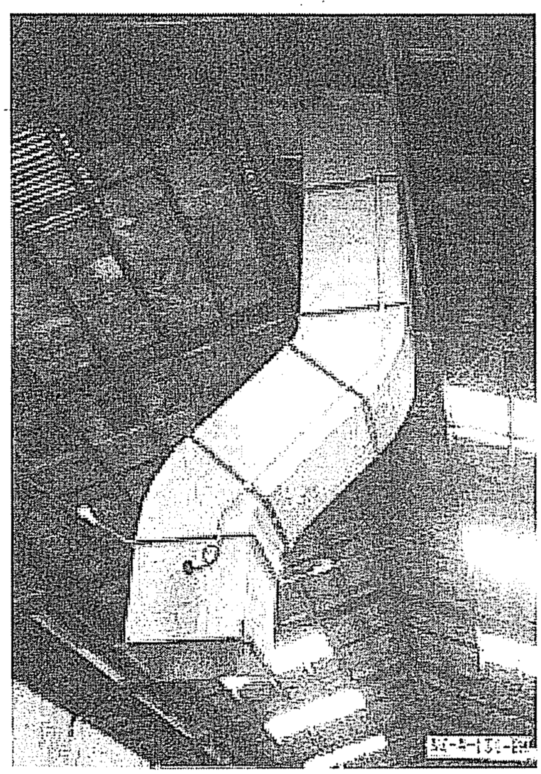


Figure A-3
Bay Milk Products, 1987 New Zealand Earthquake. Long Vertical Cantilever Supported by the Roof at One End and Guy Wires at the Other

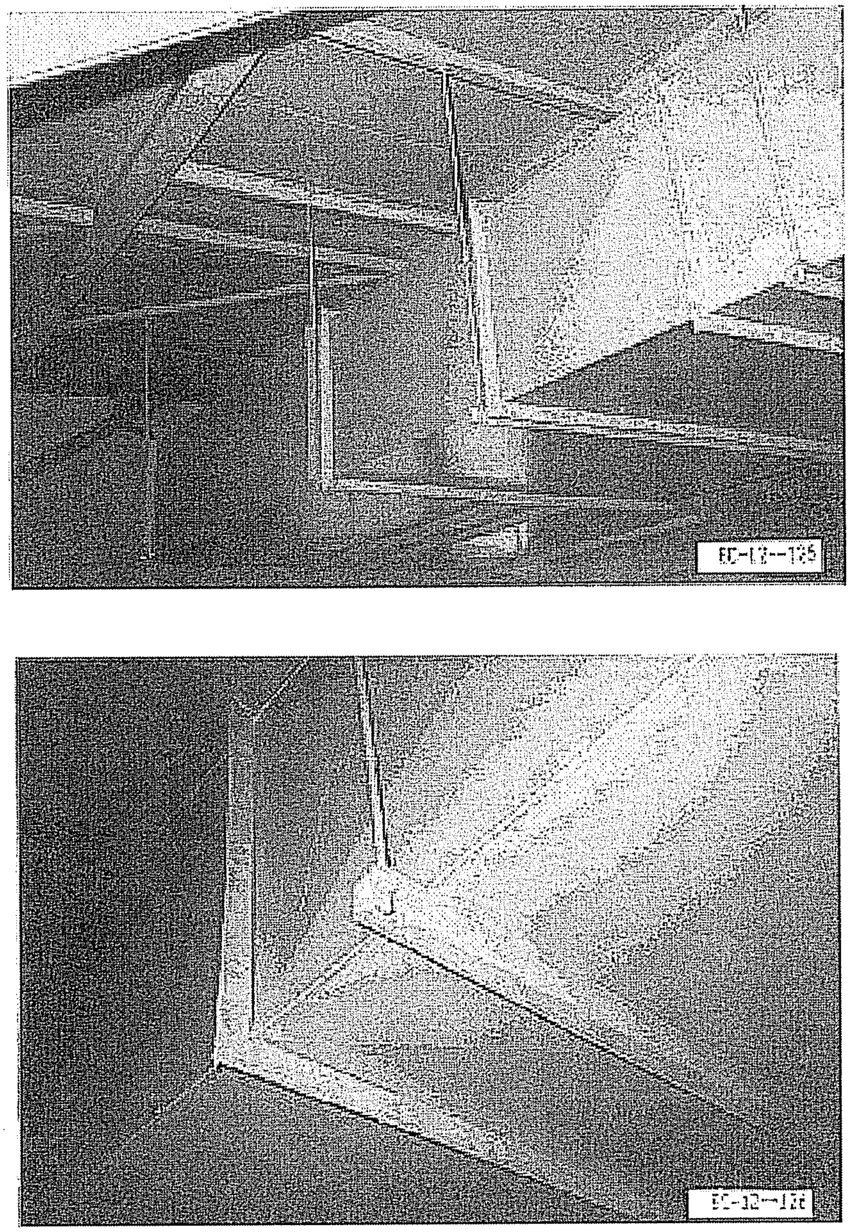


Figure A-4
El Centro Steam Plant, 1979 Imperial Valley Earthquake. Trapeze Rod-Hung Rectangular Duct With Close Up of the Trapeze Detail

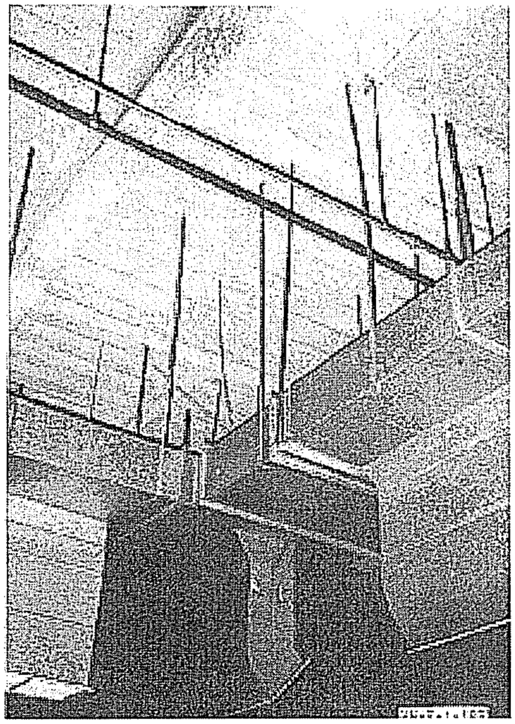


Figure A-5
California Federal Bank Facility, 1987 Whittier Earthquake. Typical Strap-Hung Rectangular Duct With Vertical Cantilevers and Diffusers

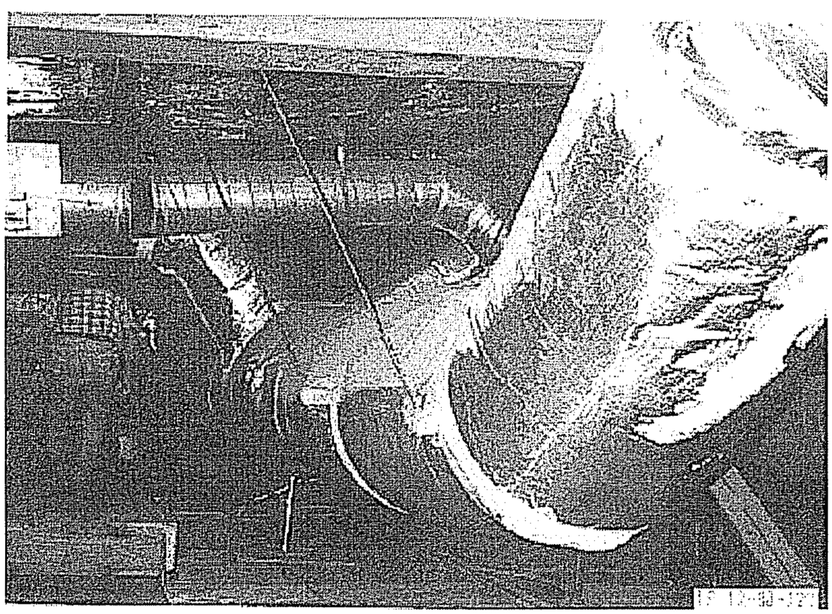


Figure A-6
Watkins-Johnson Instrument Plant, 1989 Loma Prieta Earthquake. Large, Insulated Round Duct With Branch Ducts and Cable Supports

Figure A-7
Pacific Bell Watsonville, 1989 Loma Prieta Earthquake. Run of Trapeze Rod-Hung Rectangular Duct

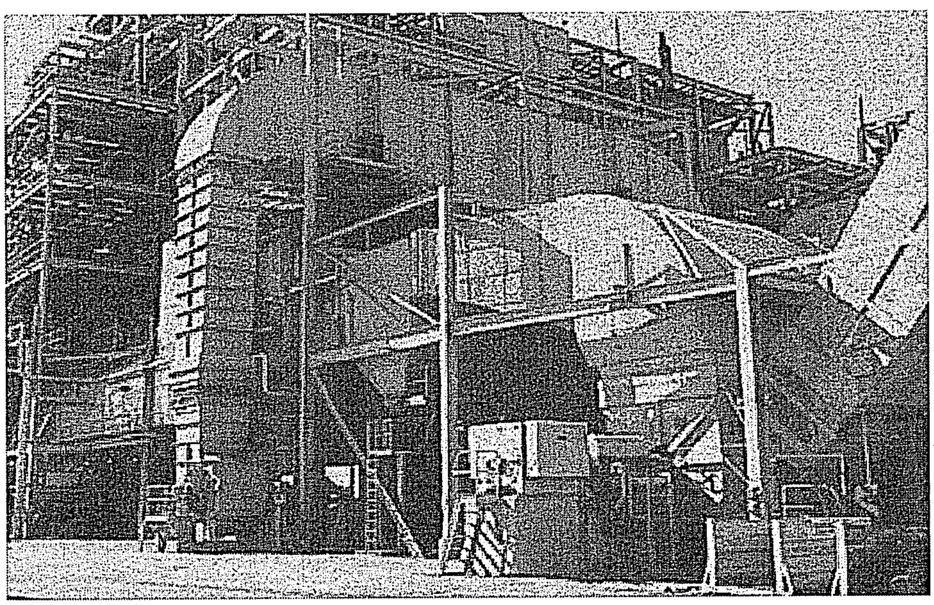


Figure A-8
Valley Steam Plant Forced Draft System, 1971 San Fernando Earthquake

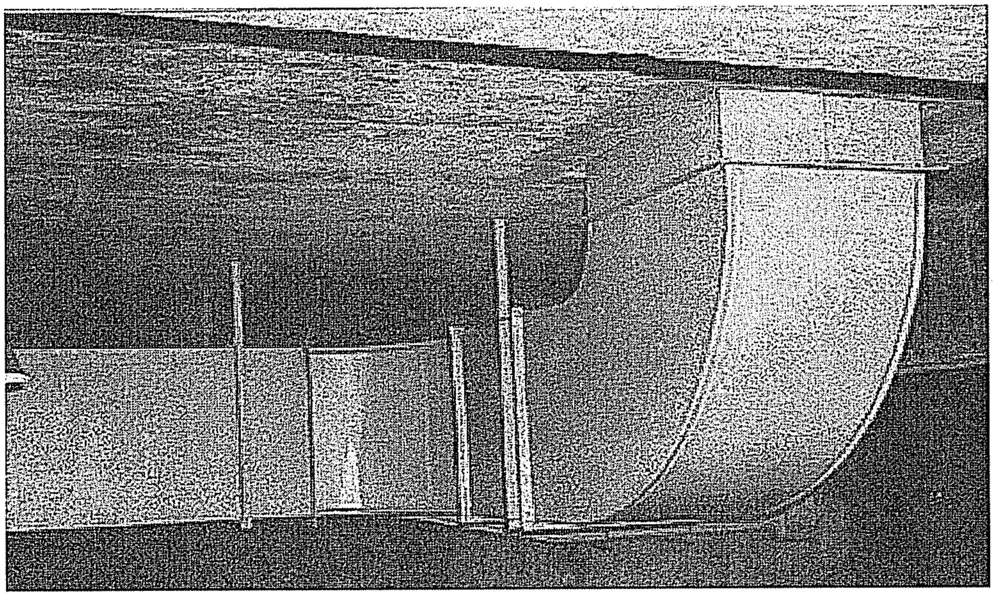


Figure A-9
Drop IV Hydro Plant, 1979 Imperial Valley Earthquake. Ceiling Mounted Ducting

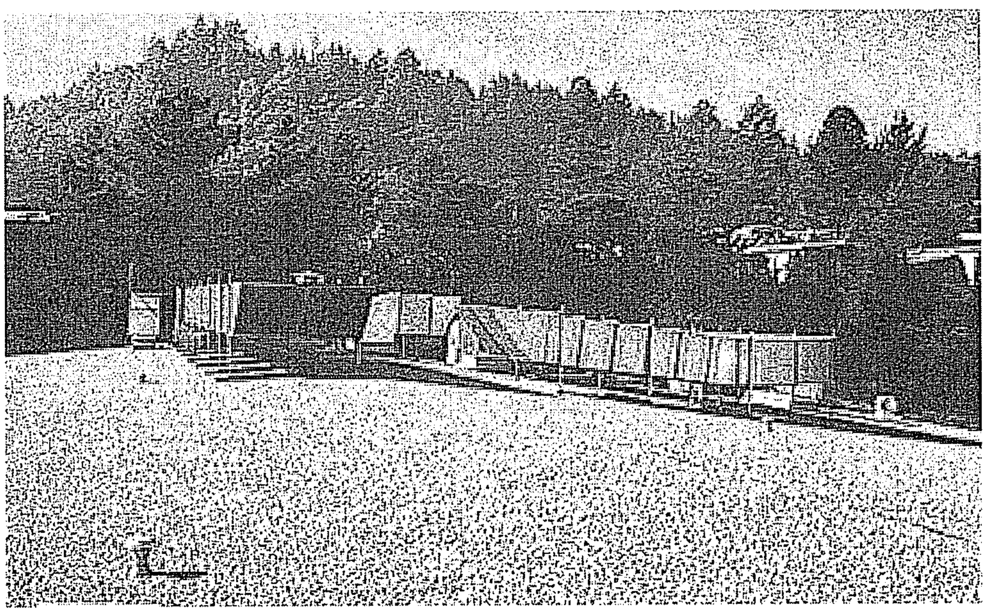


Figure A-10
Watkins-Johnson, 1989 Loma Prieta Earthquake. HVAC Ducting Atop Roof Level

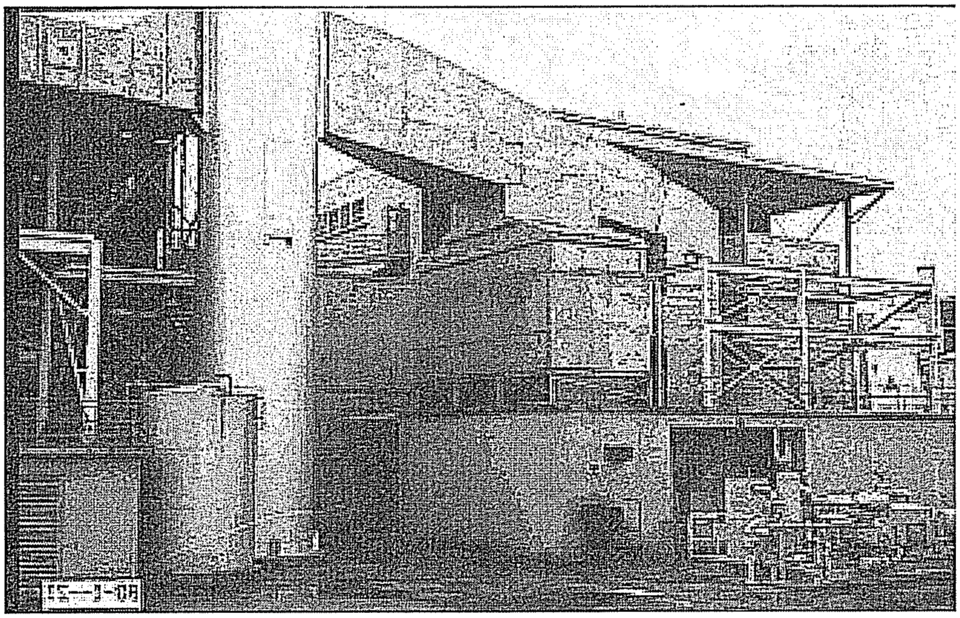


Figure A-11
Magnolia Plant, Burbank, Ducting at Induced Draft Fan, 1971 San Fernando Earthquake

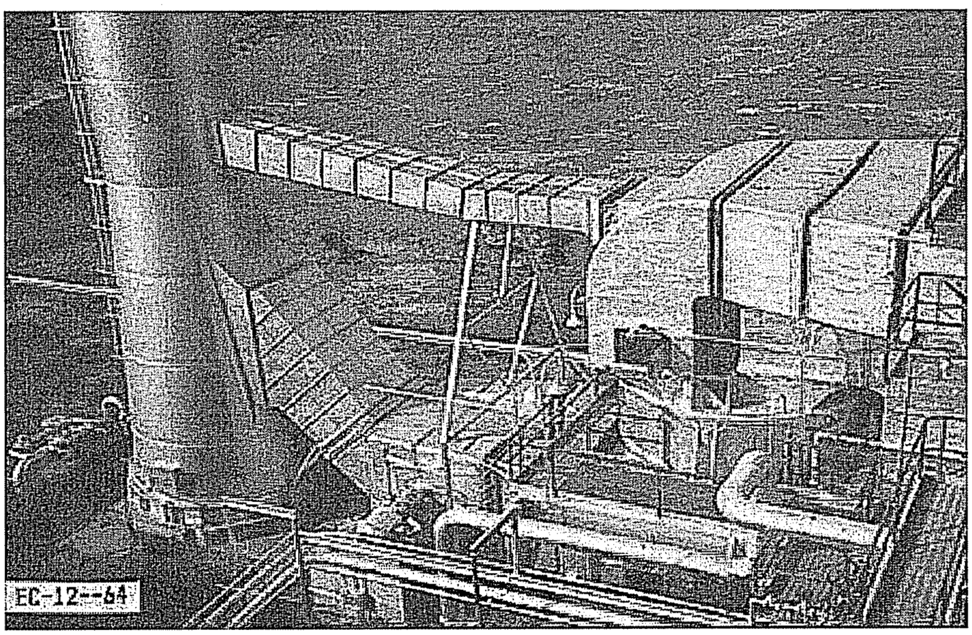


Figure A-12
El Centro Steam Plant, 1979 Imperial Valley Earthquake

It is important to note that nearly all of the HVAC duct installations in the database facilities were designed and installed without specific consideration of seismic loads. Also, some facilities were up to forty years old at the time of their earthquakes. In addition to the effects of age, the initial installation and any subsequent modifications to database ducts and their supports included all of the normal oversights and deficiencies of industrial construction.

Ductwork ruggedness was demonstrated in most instances, but there were some cases in which one or more attributes led to seismic damage. A summary, organized by earthquake, of the configurations and structural characteristics which contributed to the damage is given below.

A.2.1.1 1983 Coalinga, California Earthquake

The Coalinga, California earthquake occurred at about 4:43 P.M., local time, on May 2, 1983, and had a Richter magnitude of 6.7. It was centered near the town of Coalinga which is midway between San Francisco and Los Angeles. Coalinga is situated in a large oil field that includes numerous petrochemical and other industrial and power installations.

Gates Substation is located on the 500 kilovolt (kV) intertie that runs north to south through the California Central Valley. The facility has two control buildings, several shops, and storage buildings. All of these structures are one-story structures of reinforced concrete block or precast concrete construction. All were designed to the seismic standards of the concurrent Uniform Building Code, seismic zone IV, or more stringent requirements imposed by the operating facility.

Gates Substation is located about fourteen miles southeast of the main shock's epicenter, and about an equivalent distance south of the nearest strong motion record at Pleasant Valley Pumping Plant. Standard ground motion attenuation formulae indicate a PGA of approximately 0.25g for the site's distance from the epicenter.

During the earthquake, a HVAC diffuser fell from a suspended ceiling. The diffuser was slipped into place and supported from the ceiling, but was not attached to the HVAC ducting (see Figure A-13).

Figure A-13
Gates Substation, 1983 Coalinga Earthquake. A HVAC Diffuser Fell From the Suspended Ceiling

A.2.1.2 1984 Morgan Hill, California Earthquake

The Morgan Hill, California, earthquake occurred on the Calaveras fault at 1:15 P.M., PST on April 24, 1984. The Richter magnitude 6.2 earthquake was centered approximately ten miles due east of San Jose. Despite localized pockets of damage to residences and commercial facilities, the damage to structures was generally light.

Wiltron, located on Mast Street in Morgan Hill, manufactures microwave and communication equipment for telephone and other companies. The facility is housed in a reinforced concrete tilt-up building which has a plywood diaphragm roof. Based upon the nearest recording instruments at Anderson Dam and the nineteen mile distance to the epicenter, the site experienced an estimated PGA of 0.35g.

At the Wiltron Facility, a four foot long vertical cantilevered section of HVAC ductwork broke from its supporting header and fell to the floor (see Figure A-14). The round duct was constructed of riveted lap joints which failed under the cantilever's inertial loads.

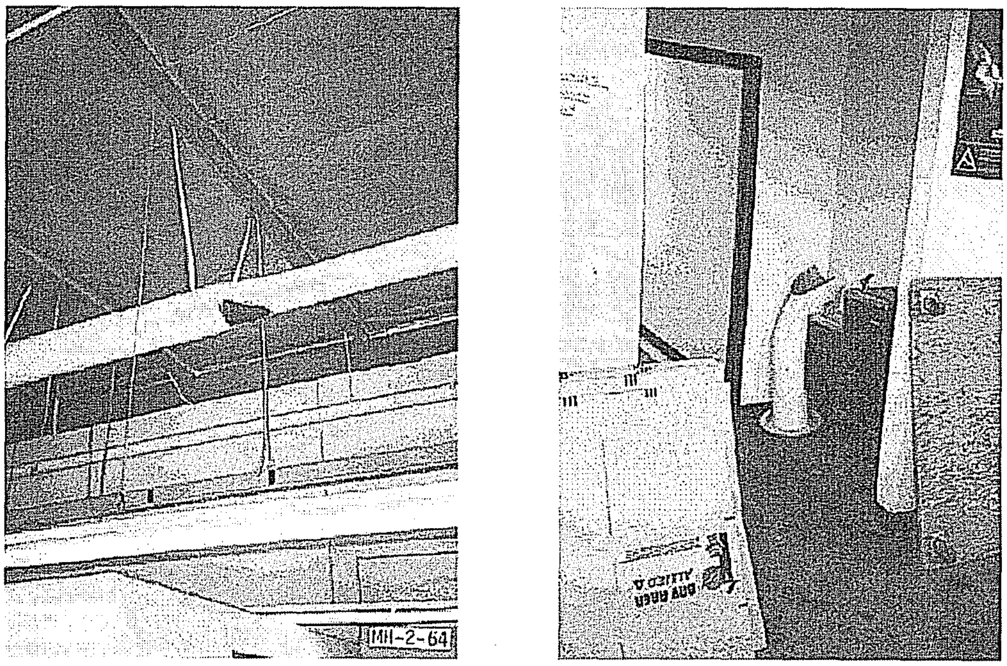


Figure A-14
Wiltron Facility, 1984 Morgan Hill Earthquake. A 4-Foot Long Vertical Cantilever Broke From its Supporting Header and Fell

Another section of HVAC duct at the same facility split a seam where a branch line entered a wall penetration (see Figure A-15). The damaged section was approximately ten inches in diameter, branching off of an estimated twenty inch diameter header. The seam pulled apart near the wall, approximately four feet from the branch point. The branch apparently was not flexible enough to accommodate the header motion, and the seam was too weak to resist the imposed differential displacement.

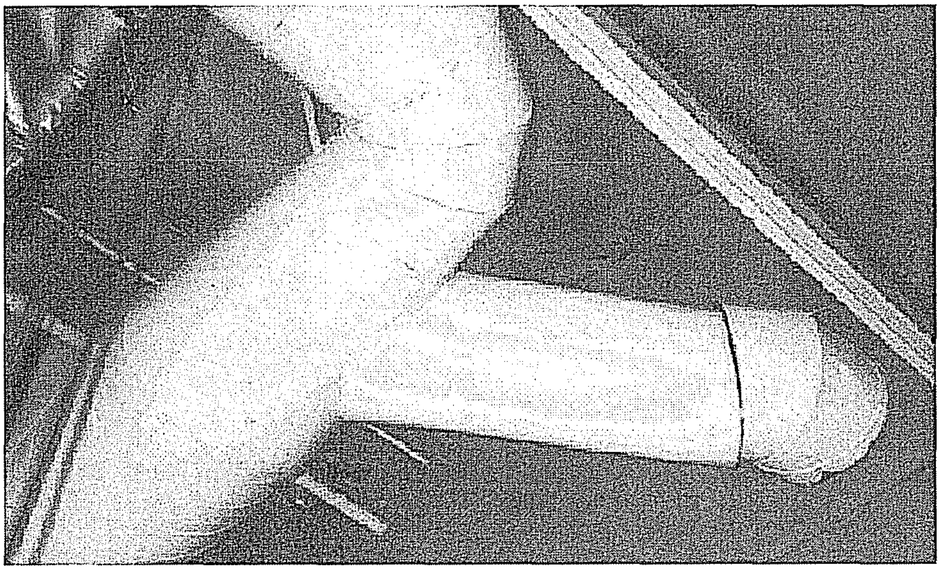


Figure A-15
Wiltron Facility, 1984 Morgan Hill Earthquake. A Branch Line Tore at a Wall Penetration Due to Flexible Header Motion

A.2.1.3 1985 Mexico Earthquake

The Richter magnitude 8.1 earthquake of September 19, 1985 was centered near a large industrial area at Lazaro Cardenas on the west coast of Mexico. The industrial area includes a large steel mill and a fertilizer plant, as well as several other manufacturing and service facilities. The industrial area is served by two large hydroelectric plants located on the Rio Balsas. Both the power plants and the industrial facilities are relatively new, having been constructed primarily in the 1970s and 1980s.

The Fertimex facility is a large fertilizer plant on an island at the mouth of the Rio Balsas. Reconnaissance teams observed several sand boils and settlement as large as twelve inches on the island. The site's PGA is estimated at 0.25g based upon the nearest ground motion records at Zacatula; however, the section of the island which supports Fertimex's Packaging Plant is thought to have experienced at least 0.50g.

HVAC ducting was damaged on the second floor of the packaging plant's switchgear building. The second floor slab is approximately fifteen feet above grade. The two-story concrete-frame structure is about 120 feet long, fifty feet wide, and has eccentric rigidity due to the asymmetric location of brick in-fill and partial concrete walls. The eccentricity created high torsional accelerations in some regions of the structure. In one of these areas, the last section in a long duct run jumped off the final support. The resulting cantilever failed at an adjacent support (see Figure A-16). The HVAC duct section was of pocket lock construction and was not positively attached to the rod hung trapeze support. Had it been attached, the damage would likely have been avoided. Also in the same area, one of the duct's rod supports pulled its expansion anchor from the concrete ceiling. The concrete quality was questionable and the ribs on the non-drilling shell anchor's cone expander were flat rather than slanted.

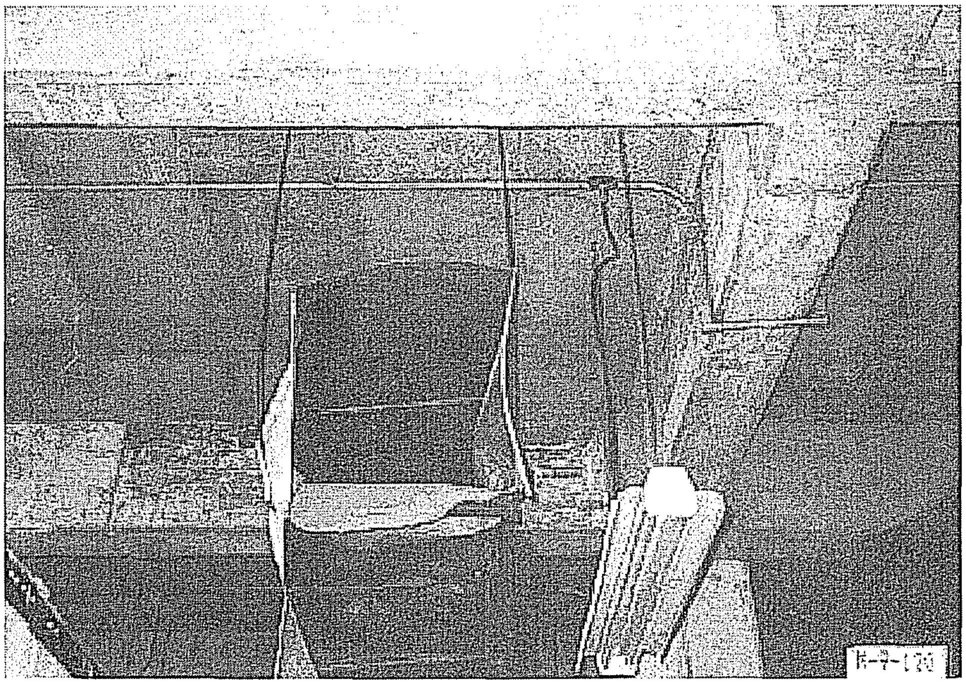


Figure A-16
Fertimex Packaging Plant, 1985 Mexico Earthquake. A section of Duct Tore when the Duct Jumped off the Final Support in a Long Run

A.2.1.4 1987 New Zealand Earthquake

On March 2, 1987 at 1:43 P.M., a Richter magnitude 6.2 earthquake struck the eastern Bay of Plenty region of North Island, New Zealand. The earthquake was preceded at 1:36 P.M. by a M5.2 foreshock and followed at 1:52 P.M. by a M5.2 aftershock. The main event, centered about four miles northwest of the small town of Edgecumbe, propagated along a previously unmapped fault that opened a large surface rupture and caused widespread soil failures. Strong ground motion also affected the nearby towns of Kawerau, Te Teko, and Whakatane. An average horizontal PGA of 0.26g was recorded approximately six miles from the rupture, and PGAs from 0.30g to 1.0g were estimated in the affected area.

The Caxton Paper Mill is located on the outskirts of Kawerau, about five miles from the fault and along a line extending in the direction of surface rupture. Based upon the ground motions recorded at the Matahina Dam and a comparison of the Modified Mercalli intensities for the dam and the paper mill, the mill's PGA is estimated to be 0.40g.

The facility's paper machine buildings (Nos. 2 and 3) are flexible high-bay steel frames and reportedly deflected excessively during the earthquake. Damaged HVAC duct was found in both buildings.

At Paper Machine Building No. 2, there were several instances of sheared ductwork joints; however, no sections fell to the floor. The circular duct was mounted near the ceiling and constructed of riveted lap joints (see Figure A-17).

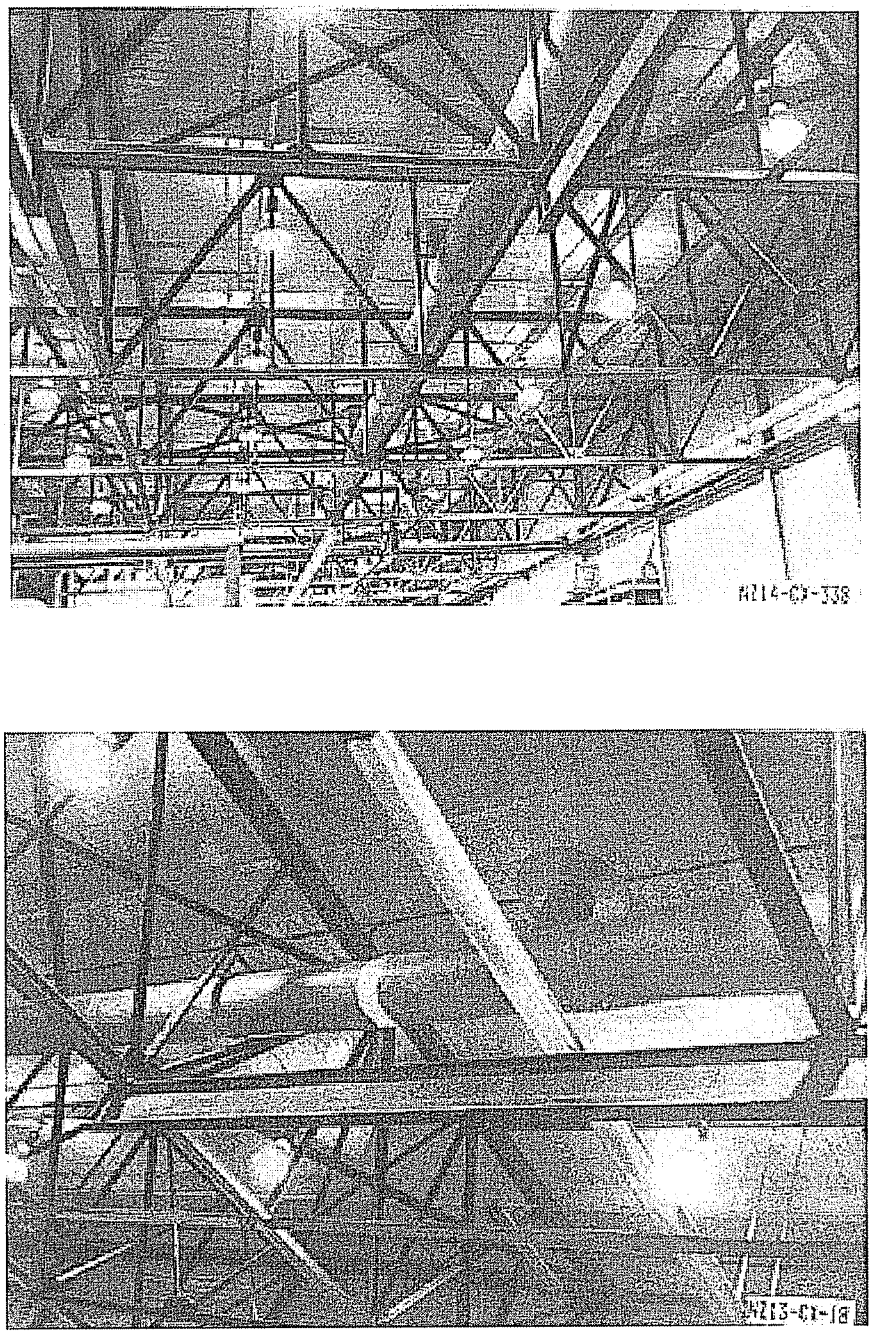


Figure A-17
Caxton Paper Mill, 1987 New Zealand Earthquake. A long, Unrestrained Run of Duct Constructed of Riveted Lap Joints (Top) and a Taped Repair of a Sheared Joint (Bottom)

Paper Machine Building No. 3 is taller and experienced more damage. The round ductwork was fastened by riveted lap joints and supported from the roof truss with rod hangers and beam clamps. Large deflection of the ductwork pulled adjacent sections of ducting apart allowing a portion to pry itself away from the supports and fall to the operating floor. Inspection of the fallen ductwork noted heavy corrosion at the riveted joint.

A.2.1.5 1987 Whittier, California Earthquake

On Thursday, October 1, 1987, at 7:42 A.M., a Richter M5.9 earthquake occurred due east of Los Angeles near the city of Whittier, California. The shock caused damage over a large area of the Los Angeles Basin. The main shock was followed by numerous aftershocks, including a M5.5 aftershock at about 3:00 a.m. on Sunday, October 4, which further damaged structures already weakened by the initial shock.

The City of Commerce Refuse-to-Energy Plant is located approximately seven miles southwest of the epicentral area. The plant was constructed in 1985, and its buildings were designed according to the current Uniform Building Code for seismic zone IV. The 11.5 MW plant is housed in a large steel-frame structure, including an enclosed high-bay refuse storage pit, with adjoining office complex, open turbine deck, and open steel-frame boiler tower. The PGA is estimated as 0.40g, based upon the records at the Bulk Mail Center and a comparison of the Modified Mercalli Intensities at similar sites. The Bulk Mail Center is less than a mile south of the plant and has similar soil conditions.

Damage to the Commerce Energy Plant was minimal but included a HVAC diffuser which fell in an office area. The diffuser was apparently not secured to the duct main run.

The main office of the Southern California Edison (SCE) Headquarters is located within a mile of the epicenter and has ground motion equipment located on site. The four-story concrete shear wall structure endured a PGA of 0.42g and sustained the most significant structural damage of the three buildings in the complex. A HVAC fan in this building dislodged from its spring isolators and displaced enough to tear the flexible bellows coupling to the duct on its discharge side. A HVAC duct was dented, but not torn, by impact from adjacent fixtures (see Figure A-18).

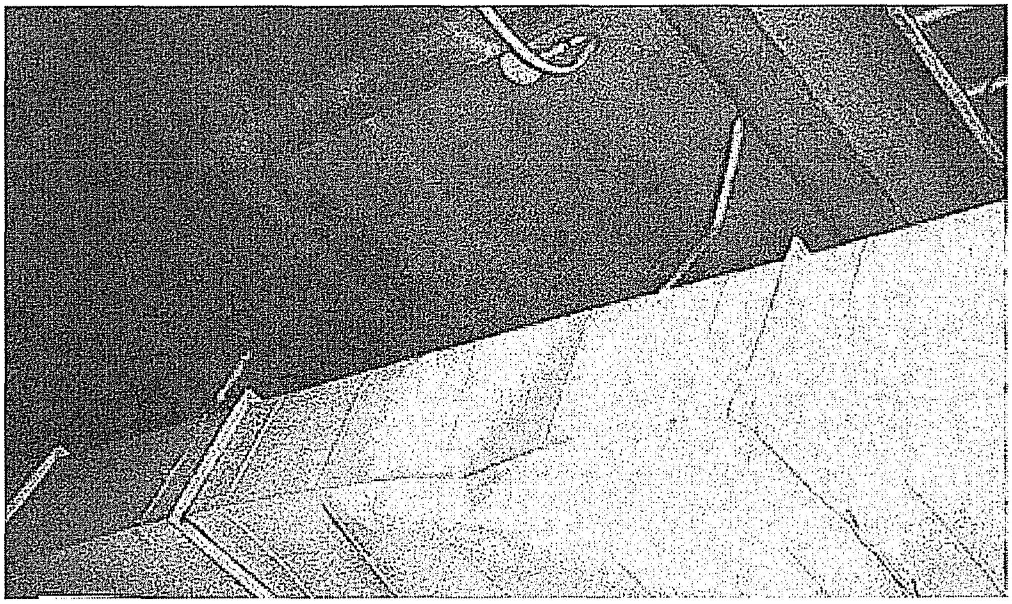


Figure A-18
SCE Rosemead Headquarters, 1987 Whittier Earthquake. HVAC Dented From Sway of Adjacent Fixtures

The Ticor Data Processing Center is a two-story concrete tilt-up building constructed around 1980. It is a somewhat complicated structure combining steel and reinforced concrete internal framing with a spancrete second floor, a metal roof deck, and exterior concrete wall panels. The building suffered substantial damage, including shear cracks in wall panels, spalling and fracture of the second floor slab, separation of joints between wall panels and framing, and a torn expansion joint in the roof.

Nonstructural damage was also extensive and included HVAC duct. Roof-mounted HVAC equipment at Ticor was severely damaged and the system was shut down. Most of the equipment was mounted on vibration isolators without lateral (seismic) restraints. Two axial fans had shifted off their mounts, rupturing their duct attachments (see Figure A-19).

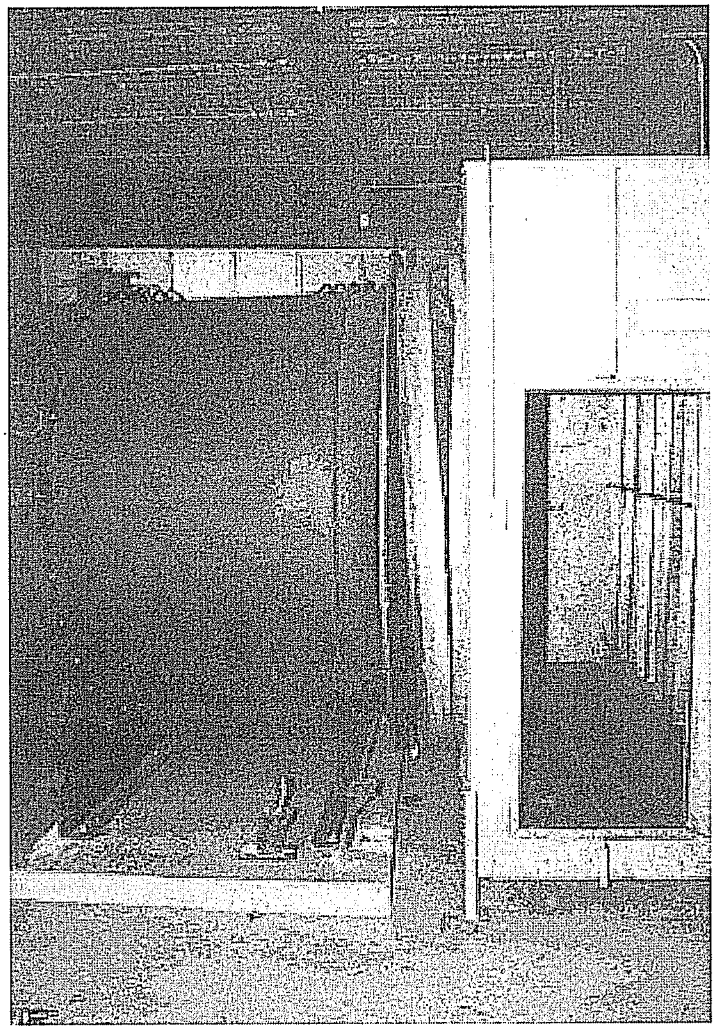


Figure A-19
Ticor Facility, 1987 Whittier Earthquake. A Flexible Bellows has Torn Due to the Motion of an Attached Fan on Vibration Isolation Mounts

The free-field record taken adjacent to the SCE Headquarters is near enough to the Ticor facility to essentially be considered a site record. Both the Ticor and SCE sites are on soft alluvial deposits laid down from the nearby San Gabriel River.

The SCE free-field accelerogragh is likely representative of the effective free-field ground motion at Ticor. Although the peak acceleration exceeded 0.40g in both horizontal directions, and the response spectra show relatively broadband frequency content, the motion was very short in duration, with only three to five cycles of significant amplitude.

The Sanwa Data Processing Center is housed in adjoining steel-frame concrete panel sided buildings of about 100,000 square feet each, on four staggered floor levels. The center contains data processing equipment mounted on raised floors, as well as office facilities. The roof includes a penthouse for HVAC equipment.

The Sanwa facility is located in the Repito Hills, a shallow formation of sedimentary rock that penetrates the surrounding alluvial valleys. The nearest record at Garvey Reservoir, with a peak horizontal acceleration of about 0.40g, is a reasonable representation of the effective free-field motion experienced by the site. The strong motion instrument is founded on compacted alluvium, less than a mile and a half from the Sanwa facility.

HVAC ducts in the space above the raised ceiling experienced movement and permanent distortion without excessive leakage, failure or loss of function. In addition, a duct above the battery racks, approximately twelve inches by twelve inches, deformed but did not fall. The long run was supported at the ceiling by sheet metal straps and had no companion angles or stiffeners. The duct deformed at the joints of an angled offset section which contained a HVAC register (see Figure A-20).

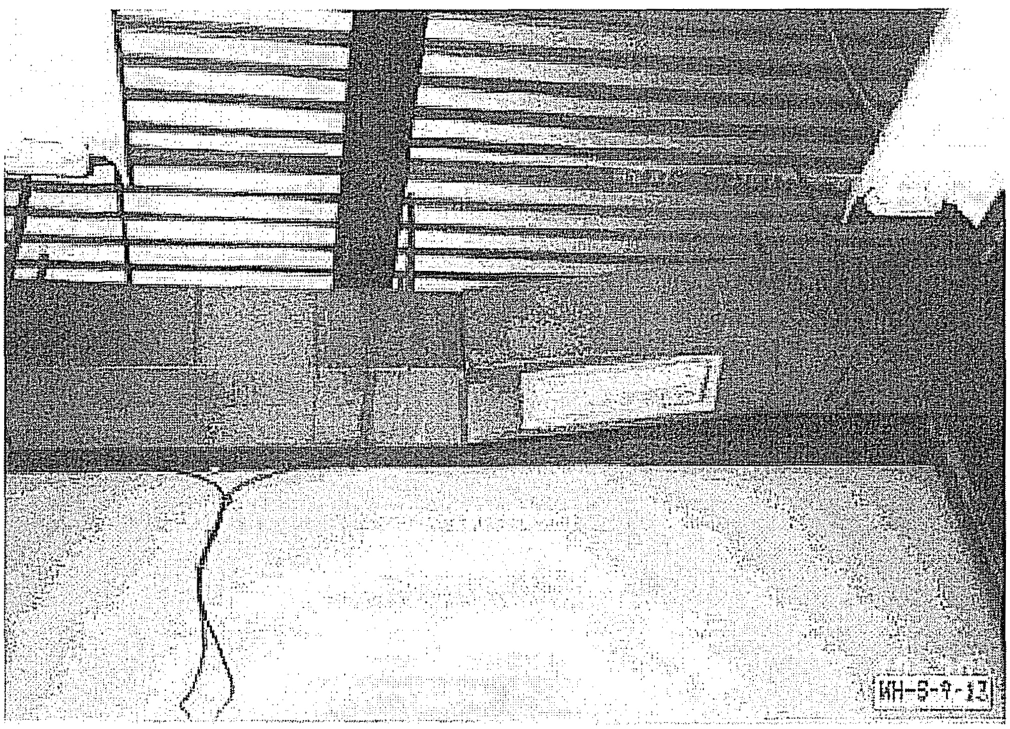


Figure A-20
Sanwa Data Processing Center, 1987 Whittier Earthquake. A Duct above the Battery Racks Deformed at the Joints of an Angled Offset Section

A.2.1.6 1988 Alum Rock, California Earthquake

The Alum Rock earthquake had a low PGA (0.15g) and relatively minor damage; however, there was HVAC related damage in the third floor mechanical penthouse of the East Ridge Mall. The damage occurred when air handling units, mounted on vibration isolation springs without lateral support, deflected and tore the attached flexible bellows to the adjacent ducting (see Figure A-21).

Figure A-21
East Ridge Mall, 1988 Alum Rock Earthquake. A Flexible Bellows Tore Due to the Motion of Attached Air Handlers on Vibration Isolation Mounts

A.2.1.7 1989 Loma Prieta Earthquake

At 5:04 P.M., Tuesday, October 17, 1989, a Richter magnitude 7.1 earthquake struck approximately ten miles northeast of Santa Cruz, California. The twenty second earthquake occurred along a segment of the San Andreas Fault near Loma Prieta. Peak ground shaking as strong as 0.65g was recorded in both the horizontal and vertical directions in the epicentral area.

The computer disk drive manufacturing plant operated by Seagate Technology is housed in a concrete tilt-up building made of adjoining one- and two-story sections. The site is located approximately two miles northwest of an instrument in downtown Watsonville. Soil conditions in the vicinity of Seagate are labeled "fluvial facies," a form of marine terrace deposits characteristic of the Watsonville area. The telephone building where the strong-motion instruments are located is embedded in flood plain deposits, unconsolidated sand and silt. The Seagate site therefore appears to be on somewhat firmer soil. Based upon the observed effects within the building, a reasonable estimate of the peak horizontal ground acceleration is 0.40g.

The sections of Seagate's circular duct are lap jointed (without rivets or bolts) and hung from the ceiling with sheet metal straps. During the earthquake, a portion of the duct fell to the floor when a strap broke at the duct connection and the attached section pulled free of its joints (see Figure A-22).

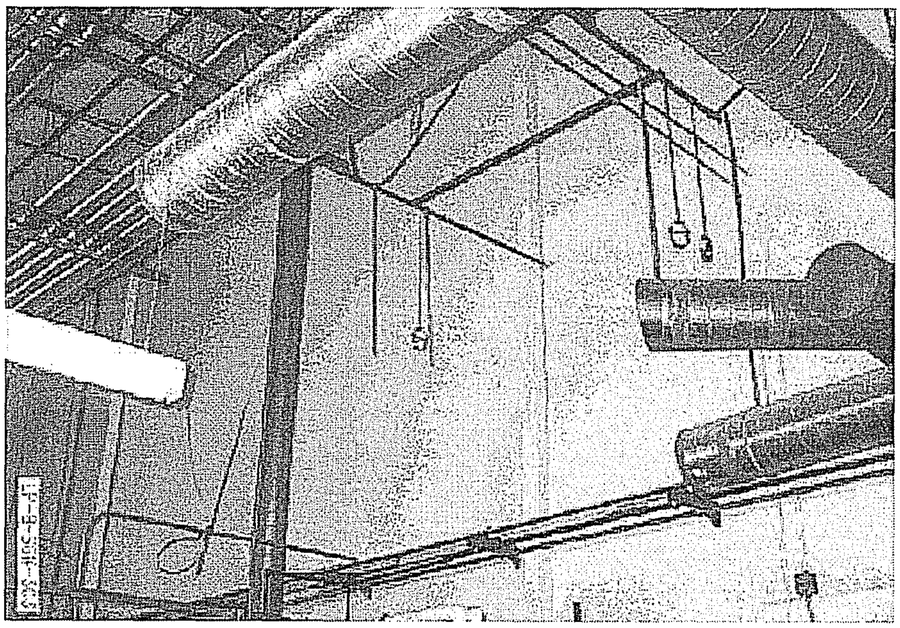


Figure A-22
Seagate Technology, 1989 Loma Prieta Earthquake. A Strap Support Broke and the Attached Duct Fell to the Floor

The Watkins-Johnson Instrument Plant is an expansion of a small instrument assembly operation that was started in the 1950s. The site includes eight buildings of various construction and vintage built into the base of hillsides within a small valley.

The nearest instruments are at the Lick Observatory (CDMG) and in the Earth Sciences Building on the University of California, Santa Cruz. Both instrument sites are just over five miles away from Watkins-Johnson and each measured PGAs greater than 0.40g. The UCSC campus instrument sites are founded on sedimentary rock whereas the Watkins-Johnson plant is in a small valley with alluvial deposits overlying sedimentary rock. The site conditions at the plant are therefore somewhat softer compared to those of the nearest instruments. Using the records and a comparison of the Modified Mercalli Intensities, the Watkins-Johnson site PGA is estimated as 0.45g.

Building number six at the Watkins-Johnson Instrument Plant is a prefabricated steel structure. Constructed in 1967, the structure has a HVAC penthouse, roughly thirty feet above grade. Inside the penthouse, the flexible bellows connecting circular HVAC ducting to an in-line axial fan tore (see Figure A-23). The duct was rod hung and the fan was supported with a rod hanger/spring arrangement. The bellows were not designed to resist the differential motion imposed by the earthquake.

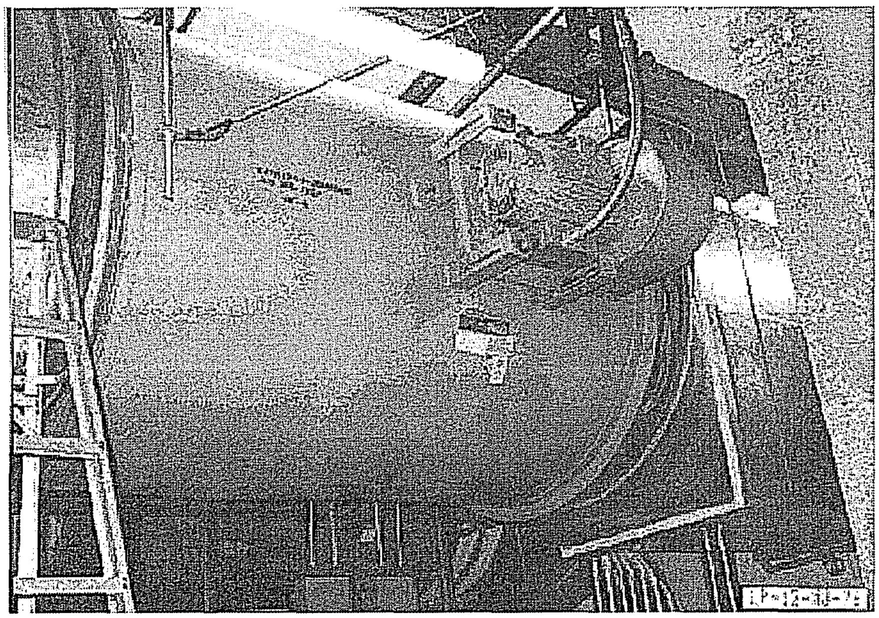


Figure A-23
Watkins-Johnson Instrument Plant, 1989 Loma Prieta Earthquake. The Flexible Bellows Connecting HVAC Ducting to an In-Line Axial Fan Tore

Also at Watkins-Johnson's building number six, the support frame anchorage for a large rectangular roof-mounted duct was distressed. The P-1000 unistrut frame and its clip angle anchorage were not designed to withstand the inertial loads. The duct was not damaged and, other than the minor anchorage distress, the support survived as well (see Figure A-24).

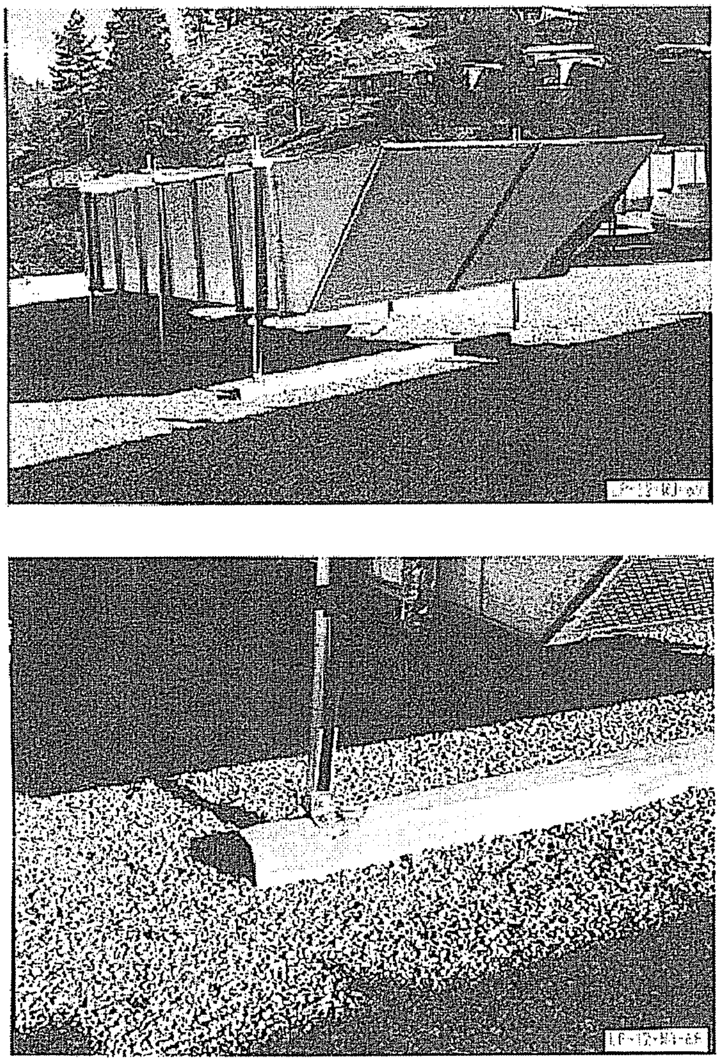


Figure A-24
Watkins-Johnson Instrument Plant, 1989 Loma Prieta Earthquake. The Support Anchorage for a Roof-Mounted Duct Was Distressed

Pacific Bell's Watsonville switching station is a four story concrete shear wall structure which endured a measured PGA of 0.33g. During the earthquake, a vertical cantilevered section of duct and its attached diffuser fell to the floor (see Figure A-25). Closer inspection revealed insufficient positive attachment between the cantilever and the header.

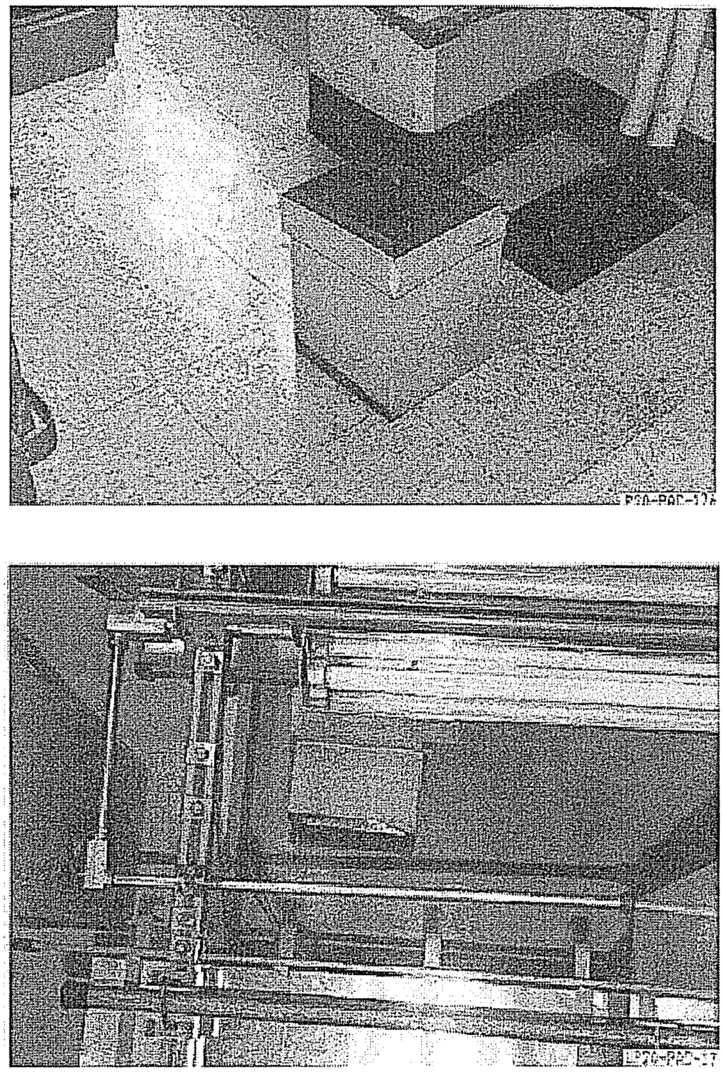


Figure A-25
Pacific Bell, Watsonville, 1989 Loma Prieta Earthquake. A Vertical Cantilevered Section of Duct Fell to the Floor With its Attached Diffuser

A.2.1.8 1990 Philippines Earthquake

On Monday, July 16, 1990, at 4:26 P.M. local time, the heavily populated island of Luzon, Republic of Philippines, was struck by an earthquake of magnitude 7.7. The earthquake was caused by major rupture along the Philippine and Digdig faults, extending approximately seventy miles along the northern edge of the Central Plains and into the Cordillera Central.

The Texas Instruments facility in Baguio City was about forty miles northwest of the epicenter in a region of extensive landslides. No accurate estimate of the ground motion exists. In one region of the facility, round, slip-jointed duct pulled apart at its seams and fell to the floor. The rod hung duct had no positive connection between sections and was attached to unanchored equipment and flexibly mounted fume hoods, creating the differential motion failure. The diffusers in the building's clean room also fell along with the room's suspended ceiling.

A.3 Summary of Observed Damage

The cases of duct system damage listed above are generally limited to direct seismic damage of the ducting or supports. The database search also uncovered a number of instances in which HVAC ducting was dented or damaged by interaction with adjacent commodities. These cases include impact with flexibly supported piping, false ceilings, and equipment. HVAC diffusers have fallen from false ceilings on several occasions, typically when the ceiling is not properly restrained against lateral motion and the diffuser is not attached to the structural slab above.

In summary, seismic damage to HVAC duct systems from the seismic experience database can be characterized as follows:

- *Broken and Fallen Cantilevered Sections.* Cantilevered sections of duct and duct diffusers constructed of riveted lap joints and simple friction connections have broken or fallen in past strong motion earthquakes. The cases of damage appear to be the result of:
  - High inertial loading of the cantilever sections causing high reaction forces at relatively weak joints
  - Flexible headers developing high seismic stresses in short duct segments not flexible enough to accommodate the motion
- *Opened and Sheared Seams.* Light gage circular duct constructed with riveted lap joints have opened up and sheared in past strong motion earthquakes. This damage has occurred at locations subject to high bending strain in very flexible duct systems.
- *Duct Fallen off Support.* The database includes one example where the end of a cantilevered duct section jumped off of its end hanger support and was damaged. The duct was not tied to the support, and was subject to high levels of seismic motion.
- *Equipment on Vibration Isolators.* HVAC duct has been damaged by excessive movement of in-line equipment components supported on vibration isolators.

B
HVAC DAMPER EARTHQUAKE EXPERIENCE DATA

Dampers are sheet metal fabricated devices that consist of a system of parallel vanes or louvers to either permit or prevent air flow. The actuators controlling the position of these louvers can be operated manually, electrically or pneumatically.

B.1 Definition of Equipment Class

Dampers are part of any heating, ventilating and air conditioning (HVAC) system, and are found at nearly all industrial sites. The principal functions of this equipment are control of air flow and isolation of HVAC systems. Some dampers at nuclear plants are used in safety related applications and must function under extreme conditions of violent weather, radiation, temperature, seismic shock, and high pressure transients (due to loss of coolant accident or tornado transient). Dampers are self-supporting structures that do not require additional integral supports or bracing. These devices are typically used in the following applications:

- Inlet or outlet side of an air handler
- In-line in HVAC ducting
- Mounted in walls to allow or prevent air flow between rooms

Dampers may be operated passively, manually, or actively. The louvers of dampers are tied together by a common linkage which is externally controlled by an electric, pneumatic or manual actuator. Typical components mounted on an air operated actuator are air tubing, flexible conduit, solenoid operated valves and pressure gages. Air receiver tanks that supply air to the solenoid valves require separate evaluation.

B.1.1 Equipment Anchorage

Dampers are an integral part of the fans, air handlers and HVAC ducting and as such are characterized as in-line components. Dampers in fans or airhandlers are part of the equipment and are evaluated with the "Rule of The Box". Some dampers such as fire dampers are mounted in walls or ceilings and therefore are not considered as in-line components. These devices are normally attached to the supporting equipment, ducting, or penetrations in walls and ceilings by bolts, rivets, or welding along their perimeter. Heavy motor-operated or pneumatic dampers typically have their own supporting system.

B.1.2 Equipment Applications

Dampers are typically operated pneumatically, electrically or manually. In the case of the pneumatically controlled and motor-operated dampers, such as flow/pressure control and isolation/shutoff dampers, a pneumatic or electrical signal is sent to the actuator to either open, close or modulate the louver position. Some dampers, such as pressure relief and tornado protection dampers, are self actuated when quick differential pressure changes are detected and use counterweights or counterbalances to return to normal position. Some fire dampers have fuseable link that would break in a fire and force the damper to close.

B.1.3 Application in Nuclear Plants

Dampers are used in all nuclear plants for control of air flow and isolation of HVAC systems. Dampers are utilized in the HVAC systems to perform one or more of the following functions:

- *Flow and Pressure Control* - Used to control a given flow rate or pressure within a system. Actuators may be electrical, pneumatic or manual.
- *Balancing* - Used to establish a flow and pressure relationship within a system. Actuation is through a manual adjustment hand-quadrant that is left at a pre-set level.
- *Isolation/Shutoff Control* - Used to isolate or seal off a portion of the system from selected flows. This type of damper is used only in an open/close application. Actuators could be electric, pneumatic or manual.
- *Backdraft Control* - Utilized where reverse flow of air is undesirable or could cause system inefficiencies. Actuation is by counterweight or counterbalance.
- *Pressure Relief* - Used to protect the system from excess pressure or damaging surges. The dampers are closed under normal conditions and open very quickly when positive pressures are detected. Actuation is by counterweight or counterbalance.
- *Tornado Protection* - Used at the intake or exhaust openings of the HVAC system. During tornado conditions this damper closes automatically. Actuation is by counterweight or counterbalance.
- *Isolation Shutoff* - Used to prohibit any leakage passing through the damper and downstream. Actuators are typically either pneumatic or manual.
- *Fire Dampers* - Mounted in walls or ceilings and is used for isolation of two separate but adjacent areas in case of fire.

B.2 Database Representation for Dampers

Figures B-1 through B-3 show typical components of dampers.

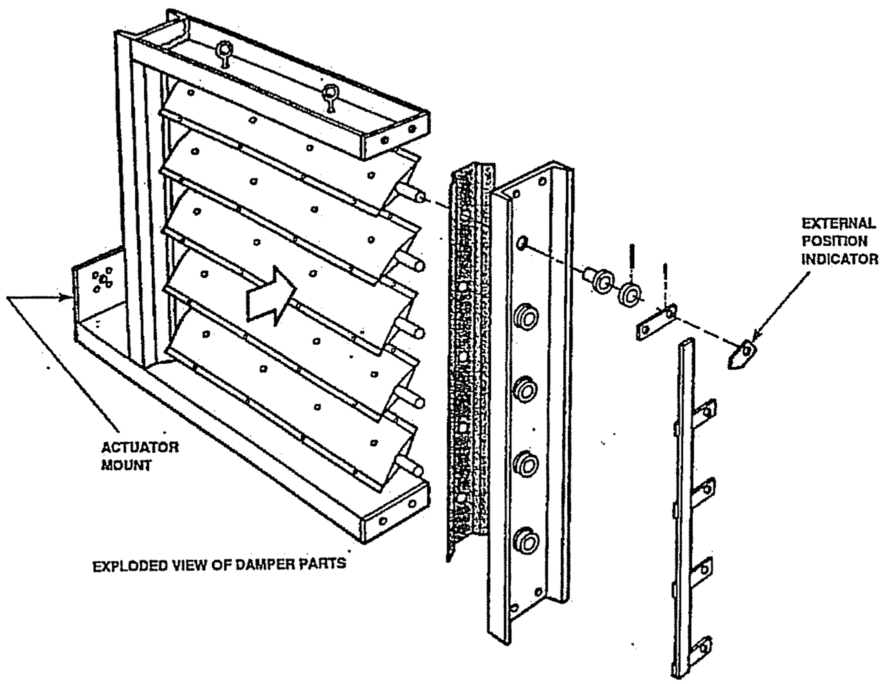


Figure B-1
Exploded View of a Typical Damper

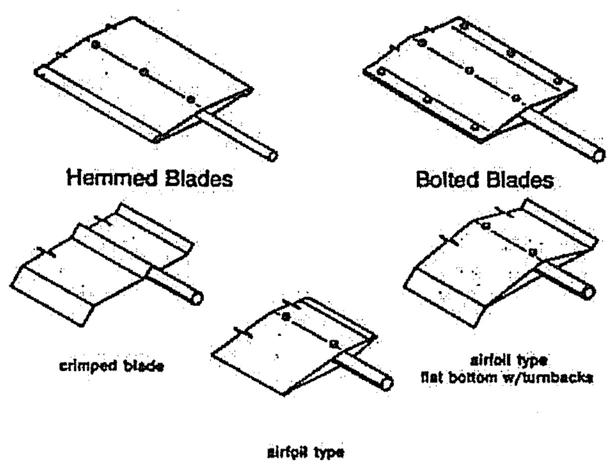


Figure B-2
Typical Damper Blades or Louvers

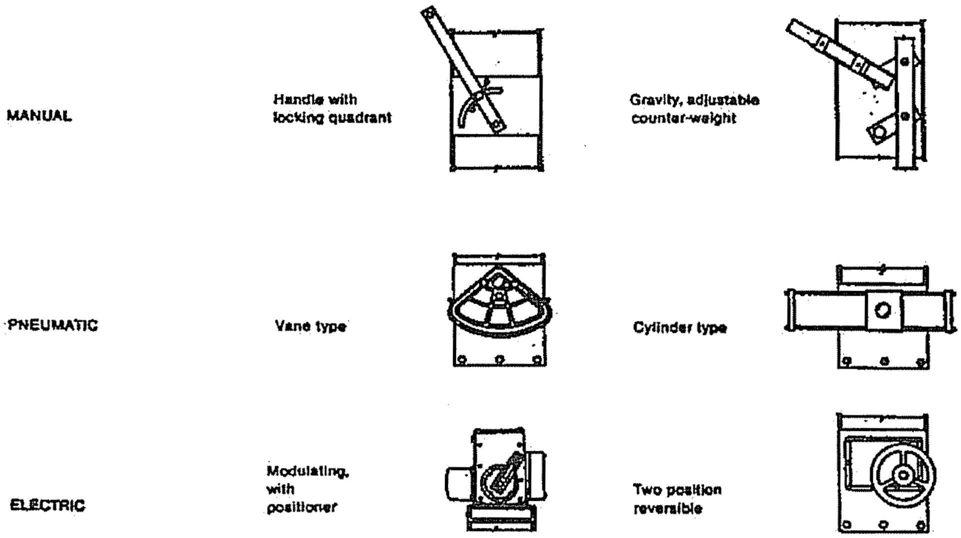


Figure B-3
Typical Damper Actuators

Figures B-4 through B-18 present examples of dampers within the database. The database inventory of dampers includes at least 175 examples, representing 20 sites and 14 earthquakes studied. Of this inventory, there are no instances of seismic damage.

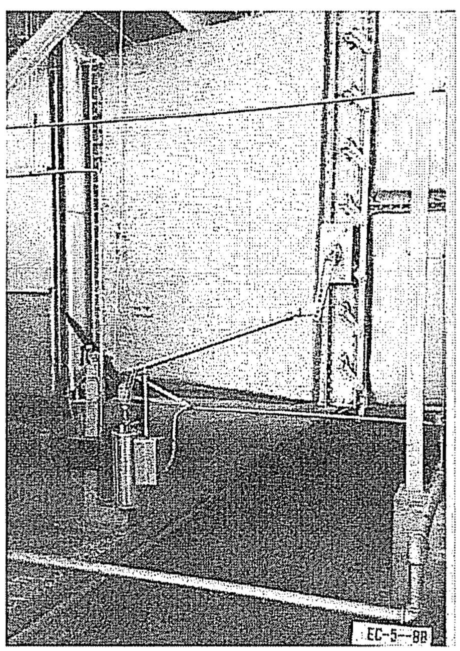


Figure B-4
Pneumatic Damper at El Centro Steam Plant Subjected to the 1979 Imperial Valley Earthquake

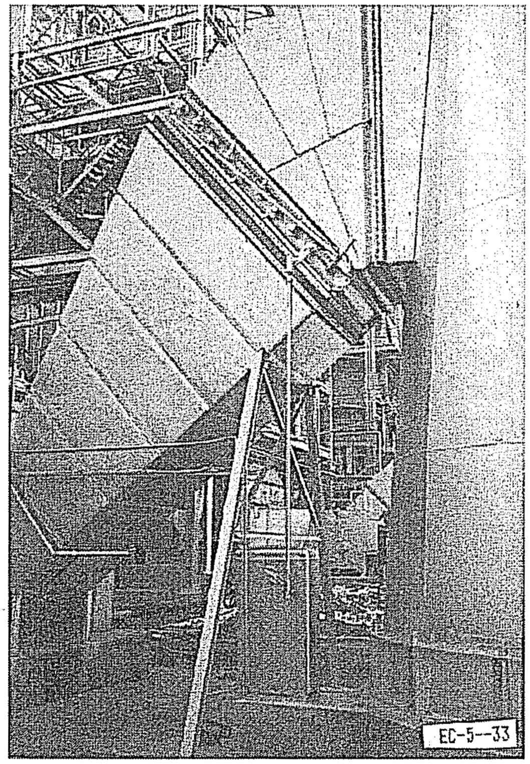


Figure B-5
Louver Style Damper on the Boiler Structure at the El Centro Steam Plant Which Experienced the 1979 Imperial Valley Earthquake

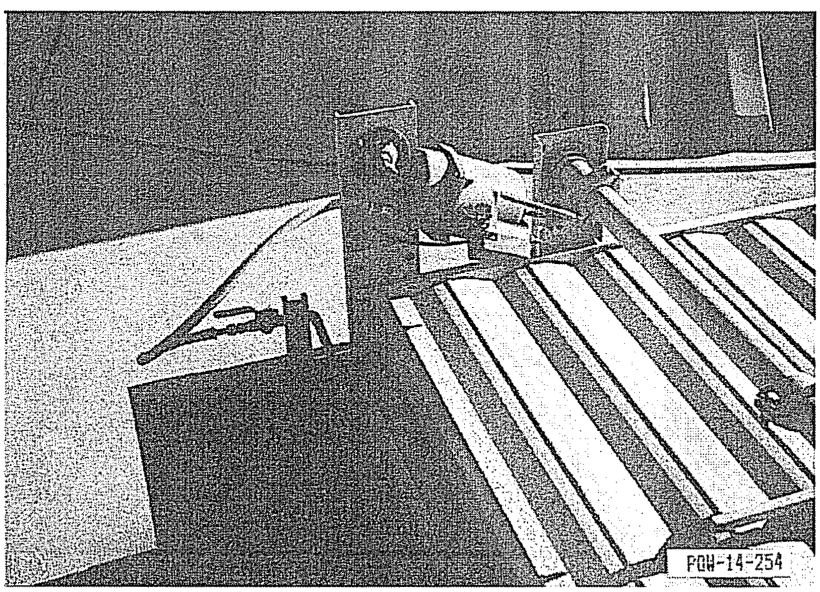


Figure B-6
Pneumatic Actuator at the Puente Hills Landfill Gas and Energy Recovery Plant

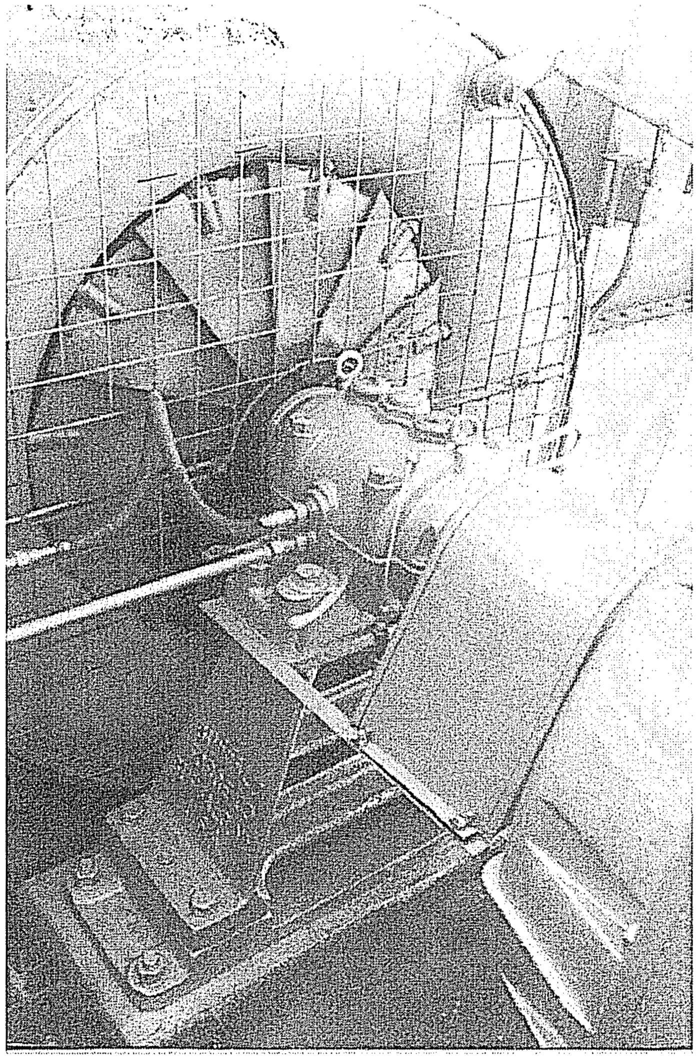


Figure B-7
Radial Type Damper at the El Centro Steam Plant Subjected to the 1979 Imperial Valley and 1987 Superstition Hills Earthquakes

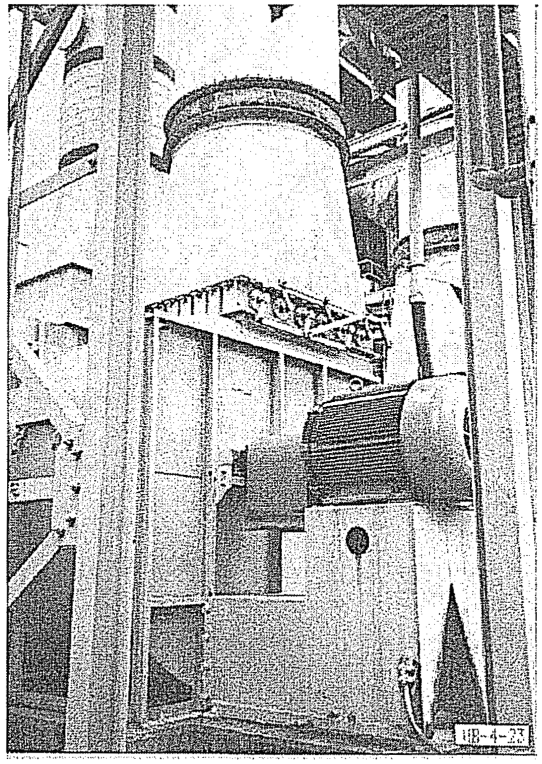


Figure B-8
Louver Type Damper at Humboldt Bay Power Plant

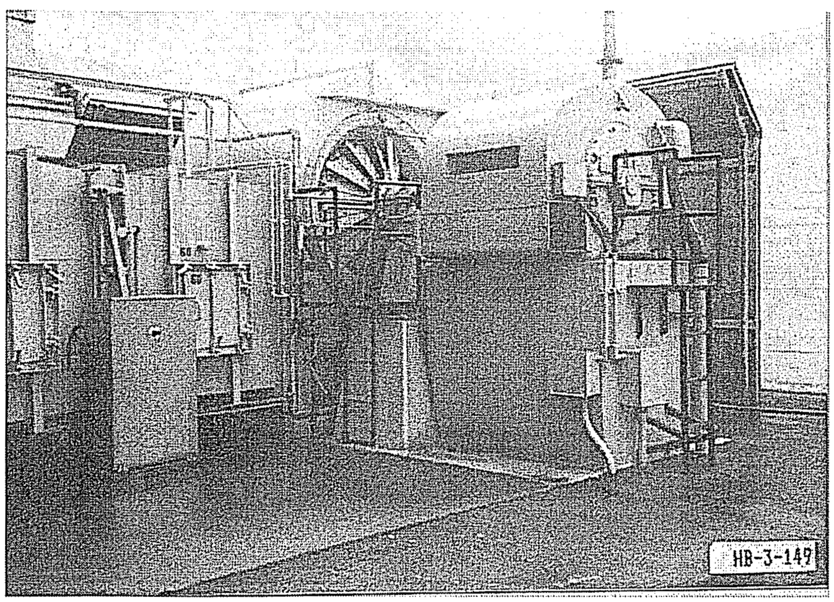


Figure B-9
Radial and Louver Type Dampers at the Humboldt Bay Power Plant, Which Experienced the 1975 Ferndale Earthquake

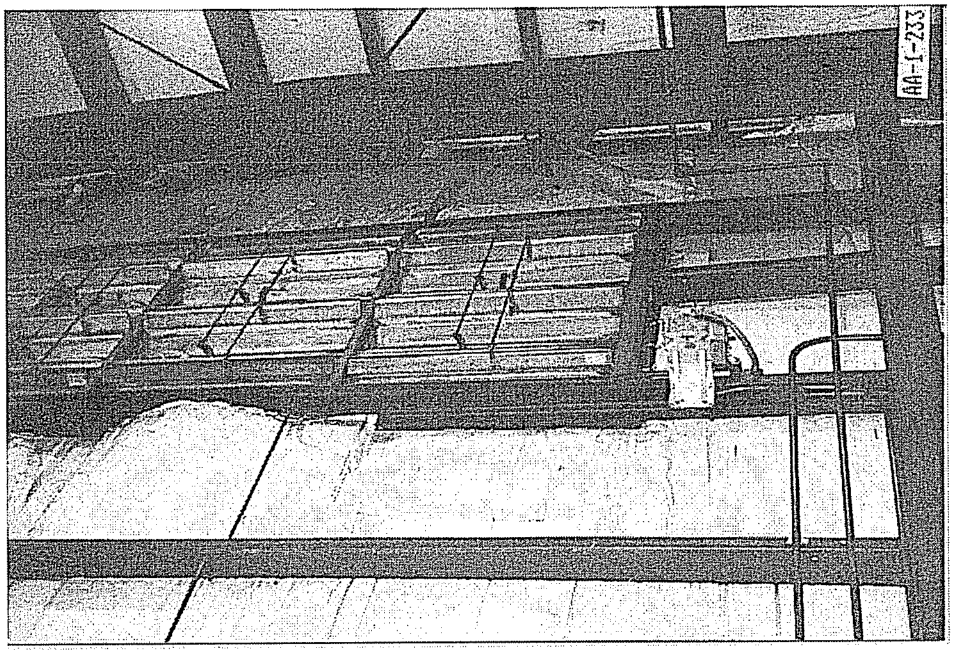


Figure B-10
Motor-operated Damper at Adak Naval Station, Which Experienced the 1986 Adak Alaska Earthquake

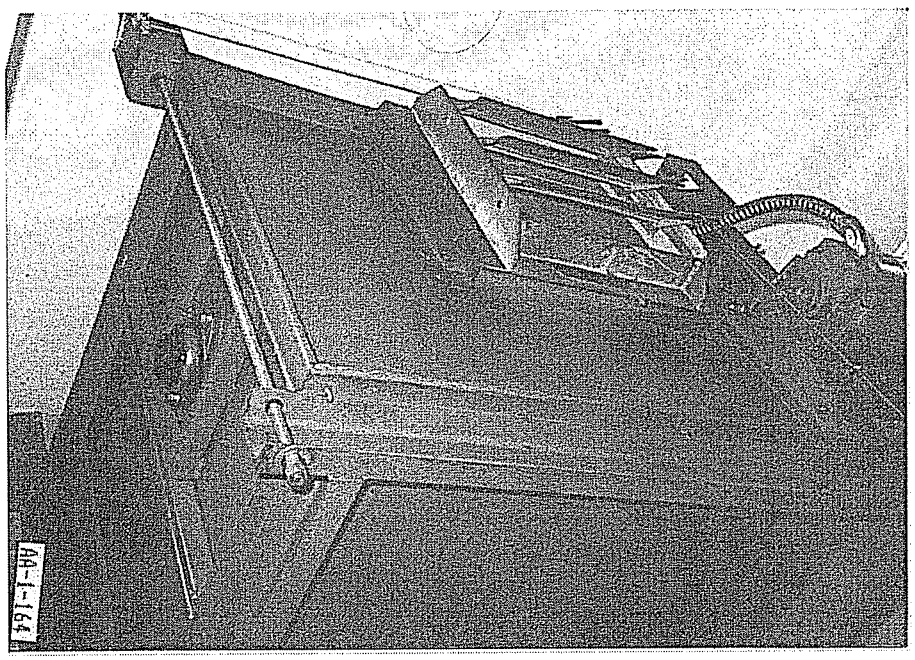


Figure B-11
Damper at Adak Naval Station

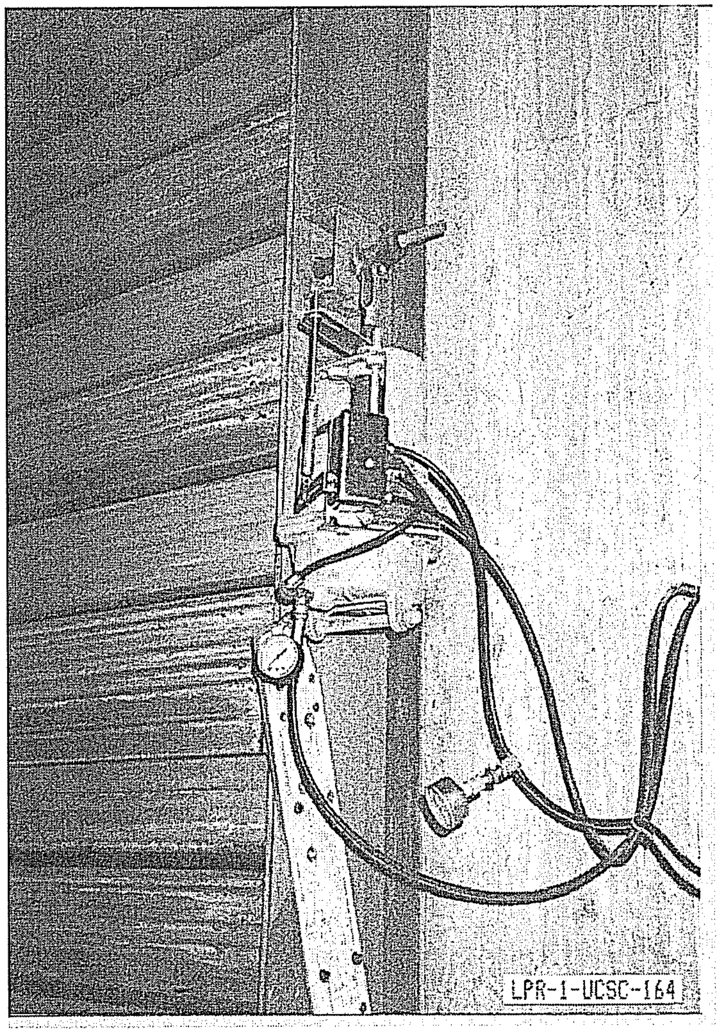


Figure B-12
Pneumatically Controlled Damper at UC Santa Cruz Applied Science Building Subjected to 1989 Loma Prieta Earthquake

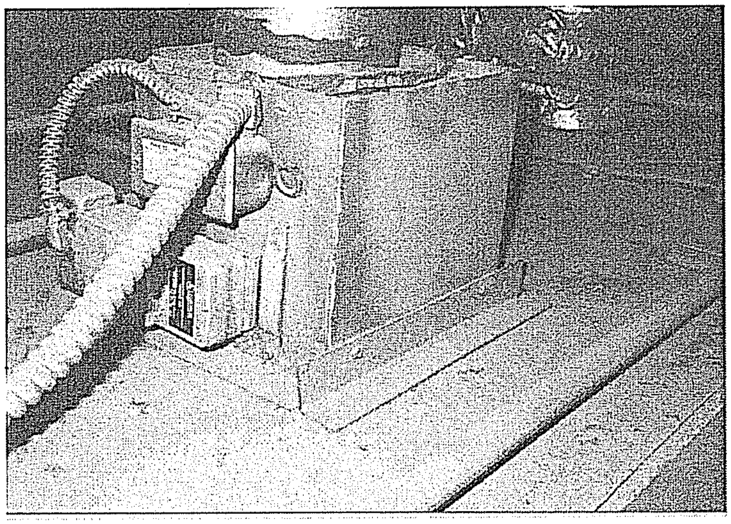


Figure B-13
Electric Motor for a Fire Damper at AES Placerita Cogeneration Plant, Which Experienced the 1994 Northridge Earthquake

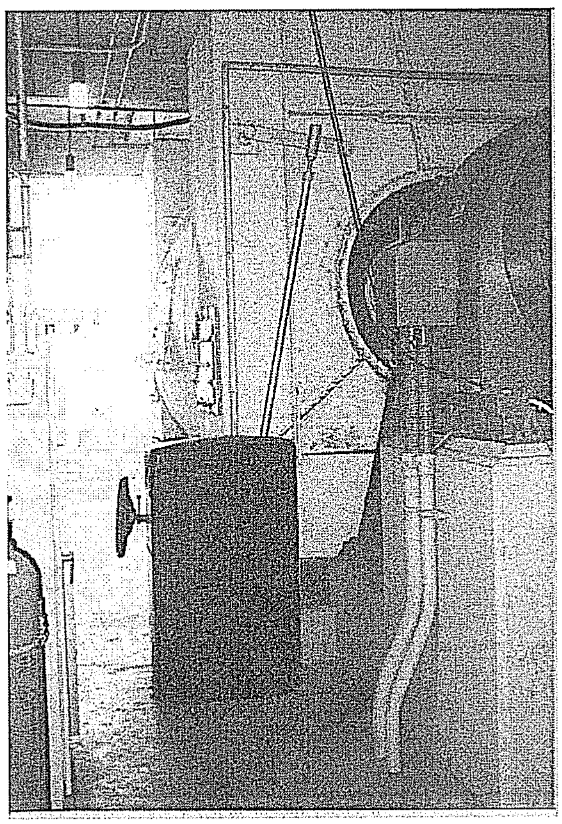


Figure B-14
Pneumatic Damper With Long Actuator at Valley Steam Plant , Which Experienced the 1971 San Fernando and the 1994 Northridge Earthquakes

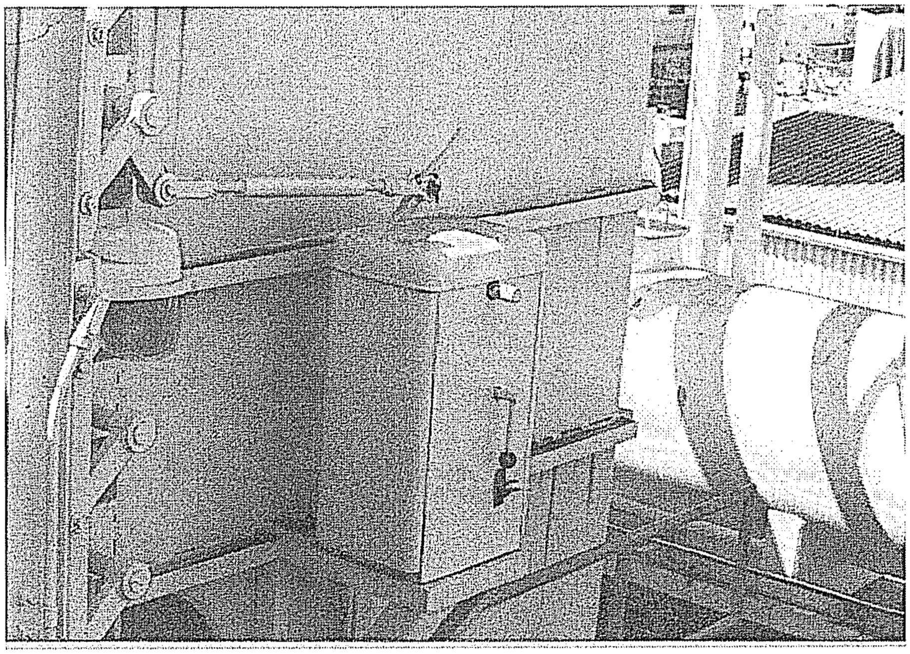


Figure B-15
Pneumatic Louver Control Damper at Pasadena Power Plant, Which Experienced Several Database Earthquakes

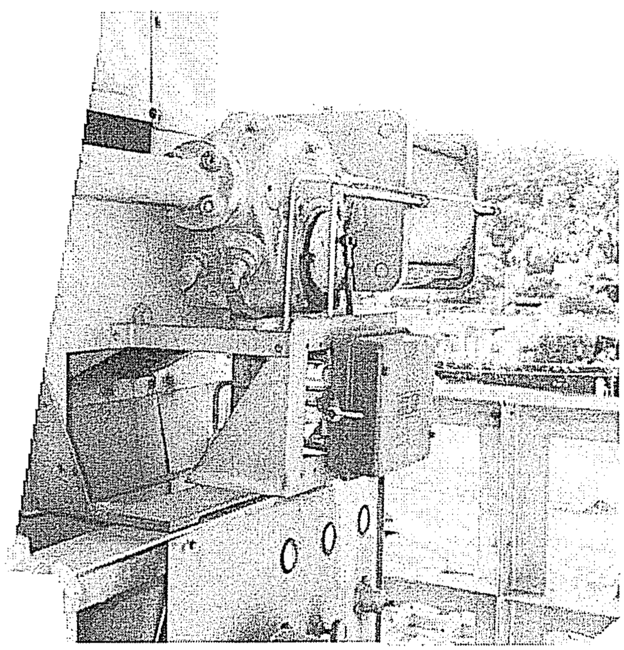


Figure B-16
Heavy Pneumatic Controller With Independent Support for a Large Damper at Pasadena Power Plant Located Very High in the Boiler Structure

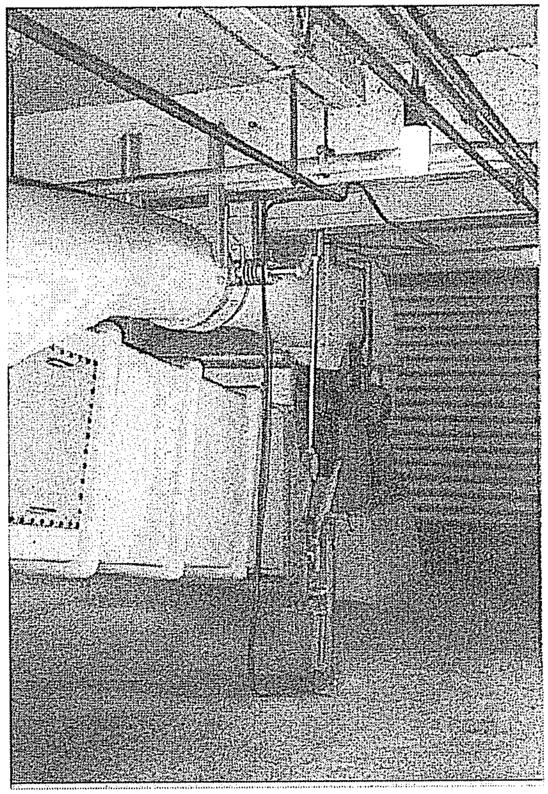


Figure B-17
Air Operated Damper With Floor-Mounted Actuator at Burbank Power Plant, Which Experienced the 1971 San Fernando and the 1994 Northridge Earthquakes

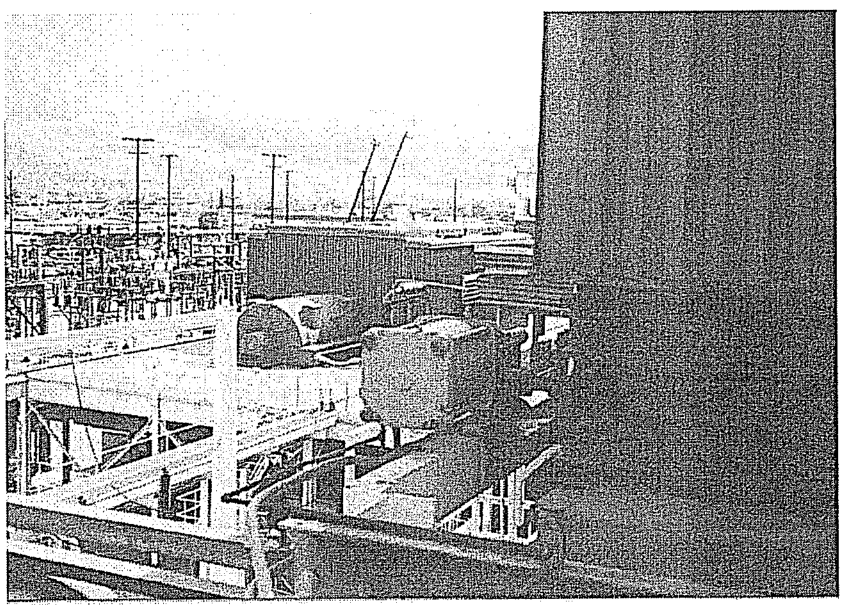


Figure B-18
Large Independently Supported Damper Controller at the Burbank Power Plant

Figure B-19 presents a bar chart that illustrates the inventory of dampers at various database sites as a function of estimated PGA.

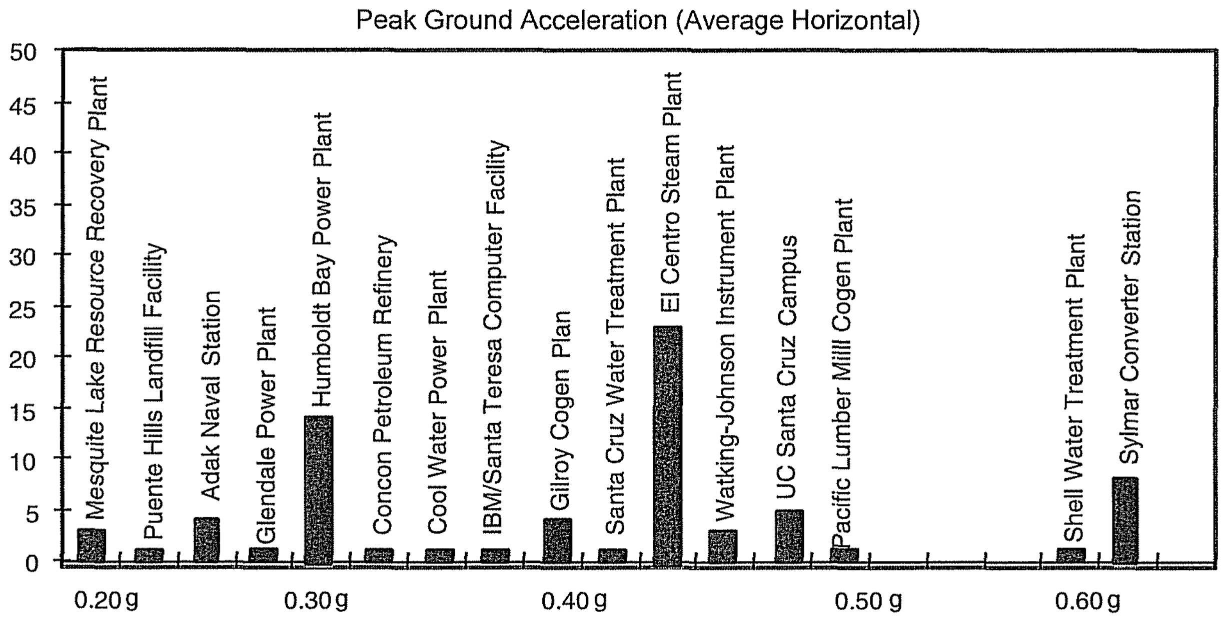


Figure B-19
Inventory of Dampers Within Experience Database

The database represents a wide variety of damper configurations. Pneumatic, motor driven and manual dampers are well represented. Some dampers in the database are housed in steel boxes which are anchored to the ground or to the building's structural steel. Heavy pneumatically operated dampers in the database have their own independent supporting system, and their usually long actuators attach to the side of the duct for louver control within the duct.

B.2.1 Basis for the Generic Bounding Spectrum

The seismic experience database includes a vast amount of data on the performance of dampers of various configurations and installations which experienced many different seismic excitation levels. The Generic Bounding Spectrum developed by SSRAP [B-2] to represent the motion at typical data sites was based on the average horizontal free field motion from each of the four reference database sites: Sylmar Converter Station (1971 San Fernando), El Centro Steam Plant (1979 Imperial Valley), Pleasant Valley Pumping Plant (1983 Coalinga), and Llolleo Pumping Plant (1985 Chile). The average of the four ground motion spectra is referred to as the Reference Spectrum. This spectrum is a conservative representation of the ground motion level to which the earthquake experience data demonstrate seismic ruggedness. In other words, the Reference Spectrum is used as a measure of the equipment capacity which has been demonstrated by experience. The Generic Bounding Spectrum is obtained by dividing this Reference Spectrum by 1.5. This 1.5 factor is to account for the possibility that floor spectra within about 40 feet above garde in the nuclear power plant might be amplified over the ground spectra more than occurred in the database plants. Thus, the resultant Bounding Spectrum is directly applicable for comparison with Ground Spectra. The capacity as defined as either the Reference Spectrum or the Bounding Spectrum, coupled with caveats on equipment attributes and installation, is then compared to the demand as defined in the GIP Table 4-1.

El Centro Steam Plant experienced a peak ground acceleration of 0.42g during the 1979 Imperial Valley Earthquake. Strong motion at the site lasted about 15 seconds. The site ground motion is based on measurements from an instrument located within 1/2 mile of the plant.

This plant includes many pneumatic and manual controlled dampers. The positioners for these dampers are enclosed in steel boxes which are then anchored to the ground or the building structural steel. There were no instances of damage to the dampers or their operators in the earthquake.

The Sylmar Converter Station located near the fault rupture of the 1971 San Fernando Earthquake, is estimated to have experienced at least 0.65g peak ground acceleration, with about 10 seconds of strong motion.

Eight instances of dampers are included in the database at this facility. None of the dampers experienced any seismic effects.

The Shell Water Treatment Plant is located about two miles north of the Main Oil Plant. The peak ground acceleration experienced at this site during the 1983 Coalinga Earthquake is conservatively estimated at 0.60g.

At this site only one documented case of a butterfly damper exists in the database. This damper remained undamaged as a result of the earthquake.

The IBM/Santa Teresa Computer Facility experienced a PGA of 0.37g, with strong motion occurring for about eight seconds during the 1984 Morgan Hill Earthquake. This facility included several motion monitors, one located in the free field 100 yards from the main building.

The database includes one pneumatic operated damper at this facility. This damper was not damaged in the earthquake.

Valley Steam Plant experienced ground shaking during both the 1971 San Fernando earthquake and the 1994 Northridge earthquake. The peak ground acceleration at the site due to each of these earthquakes was approximately 0.40g. The plant, which includes four units with a total generating capacity of 513 MW, is located about 10 miles from the epicenter and three miles from the fault of the San Fernando Earthquake.

Twenty four of the pneumatically operated dampers at this plant are represented in the seismic experience database. None of these dampers sustained any damage due to the above earthquakes.

Burbank Power Plant, located in the Burbank/Glendale area of the San Fernando Valley, is estimated to have experienced a peak ground acceleration of 0.25g, with about 10 seconds of strong motion, during the 1971 San Fernando Earthquake. This plant also experienced the 1994 Northridge earthquake with an estimated peak free field acceleration of 0.30g. This plant consists of five steam generating units and two gas turbine units.

A total of 35 pneumatically operated dampers at this site are represented in the database. No damage was reported to these dampers as a result of the above earthquakes.

Pasadena Power Plant has the unique distinction of being the only site included in the seismic experience database that has been shaken at comparable levels of intensity by four earthquakes, each producing a level of moderate ground motion comparable to a design basis event for a nuclear plant in the eastern United States. The Pasadena Plant experienced the magnitude 6.6 San Fernando earthquake in 1971, the magnitude 5.9 Whittier earthquake in 1987, the magnitude 5.8 Sierra Madre earthquake in 1991, and finally the magnitude 6.7 Northridge earthquake in 1994. The peak ground acceleration experienced by this site during these shakings is estimated to be about 0.20g.

The database includes a total of 24 pneumatically operated dampers at this facility. These dampers functioned properly during and after the above mentioned earthquakes with no damage.

AES Placerita Cogeneration Plant experienced a peak ground acceleration of at least 0.60g during the 1994 Northridge Earthquake [B-3]. The estimated site ground motion is based on measurements from several instruments located a few kilometers from the plant.

Twenty small motor operated fire dampers for Halon system isolation are included in the database for this plant. No damage, as a result of the Northridge earthquake, was reported for these dampers.

B.3 Instances of Seismic Effects and Damage

The experience database contains no instances of seismic effects to dampers. The database contains no evidence of the malfunction of dampers during or immediately after an earthquake. In addition, no instances of seismically induced damage to dampers were found in an extensive literature search. Therefore, dampers can be classified as inherently rugged equipment.

B.4 Sources of Seismic Damage

The seismic experience database indicates that dampers possess characteristics that generally preclude damage in earthquakes. The experience database contains no instances of damage or significant seismic effects to dampers or their actuators.

B.5 Caveats for Dampers

The equipment class of Dampers described below has been determined to be seismically rugged based on earthquake experience data, provided the intent of each of the caveats listed below is met. This equipment class includes all components of dampers installed in HVAC systems (or other types of duct systems). Fire dampers which are installed in walls or ceilings are also within this equipment class. Damper components are louver blades, actuators (pneumatic, electrical, and manual, as well as automatic counterweight and counterbalance actuators), attached air tubing and rigid or flexible electrical conduit, solenoid valves and pressure gages.

Dampers are sheet metal fabricated devices that consist of parallel flaps to either permit or prevent air flow. Dampers are an integral part of fans, air handlers and HVAC ducting and in case of fire dampers they are installed in walls or ceilings. The flaps or louvers of dampers are tied together by a common linkage which is externally controlled by an electric, pneumatic or manual actuator. Automatic dampers are operated by a pre-set counterweight or counterbalance.

Attachment of dampers to the HVAC ducting or equipment is through bolting, riveting or welding provided around the perimeter of the damper housing. The pneumatic or electric motors that control the actuation are typically attached to the damper housing; however, they also could be mounted on a nearby wall or floor with rack and pinion connection provided for the actuator. Dampers with heavy motor-operated actuators (typically greater than about 200 pounds) that are installed in-line in HVAC ducting are also represented in the database. This type of damper, however, should have its own independent support system.

The Bounding Spectrum represents the seismic capacity (defined as free-field motion at effective grade) of dampers when the damper meets the intent of the following inclusion and exclusion rules. Note, however, that when the specific wording of a caveat is not met, then a reason for concluding that the intent has been met should be provided on the SEWS.

DMPR/BS Caveat 1 - Earthquake Experience Equipment Class. The damper should be similar to and bounded by the DMPR class of equipment described above. The equipment class descriptions are general and the Seismic Capability Engineers should be aware that worst case combination of certain parameters may not be represented in the generic equipment class. These worst case combinations may have reduced seismic capacity and should be carefully evaluated on a case-by-case basis.

DMPR/BS Caveat 2 - Damper Operator/Actuator Not of Cast Iron. The intent of this caveat is to avoid the brittle failure mode of cast iron as evidenced by poor performance of some cast iron components in the past earthquakes. Note that the database does not contain actuators with cast iron components; therefore, it is not necessary to determine the material of the damper control components unless it appears to the seismic capability engineers to be made of cast iron.

DMPRS/BS Caveat 3 - Sufficient Slack and Flexibility of Attached Lines. Sufficient slack and flexibility should be present in attached lines (e.g., air tubing, electrical conduit) to preclude a line breach due to differential seismic displacement of the equipment and the line's nearest support. Also, for damper positioners with independent supports (i.e., not mounted integrally on the duct) the effect of differential displacement on the actuator (with actuator defined as the rod connected at one end to the positioner and at the other end to the duct louver controls) needs to be considered. The issue here is to watch out for cases where the actuator is connected to a rigidly mounted positioner at one end and to a rod hung duct system at the other.

DMPRS/BS Caveat 4 - Adequate Anchorage. Damper controls when mounted on the ground or nearby structures should be properly anchored in accordance with the guidelines of GIP section 4.4. When the motor- or pneumatic operator is mounted on the duct at the damper location the adequacy of the attachment point to the duct skin or its stiffeners should be ensured.

DMPR/BS Caveat 5 - Duct Distortion. The duct at the damper location should be carefully investigated for any signs of distortion as this would interfere with the damper operation.

B.6 References

B-1. Quality Air Design, "Design of Nuclear Dampers," Division of ACDC Inc.

B-2. Senior Seismic Review Advisory Panel (SSRAP), "Use of Seismic Experience and Test Date to Show Ruggedness of Equipment in Nuclear Power Plants," Sandia Report SAND92-0140, Part 1, 1992.

B-3. *The January 17, 1994, Northridge Earthquake: Effects on Selected Industrial Facilities and Lifelines*, Prepared by EQE International, Electric Power Research Institute, July, 1995.

B-4. *The October 1, 1987, Whittier Earthquake: Effects on Selected Power, Industrial, and Commercial Facilities*, Prepared by Electric Power Research Institute, and EQE Engineering Inc., December, 1990. EPRI NP-7126.

C

DEVELOPMENT OF ALLOWABLE SPANS FOR SHEET METAL DUCTS

Allowable span length charts for horizontal ducts with seismic loads are developed to check for conformance with SMACNA standards. These charts may be used during the in-plant screening review or to guide sample selection for analytical reviews. The screening charts consider seismic and dead weight loading; pressure loads are decoupled since they only influence duct thickness and spacing between duct stiffeners. Seismic loading consists of horizontal and vertical static approximations using peak spectral acceleration. Dead load stresses are summed absolutely with the Square Root Sum of the Squares (SRSS) of the vertical and horizontal seismic stresses. Allowable span length calculation criteria are developed using analytical requirements presented in Section 4. HVAC duct systems not meeting these spans should be selected for analytical evaluation. The process for developing allowable span charts is described below.

C.1 Rectangular Ducts

The evaluation guidelines (see Section 4) for rectangular ducts define the section property of a rectangular duct as being comprised of 2- by 2-inch angle sections at each corner. The maximum expected bending moment is approximated by:

$$M = \frac{w\ell^2}{8} \text{ (For ducts spanning over one or two spans)} \qquad \textbf{Eq. C-1}$$

$$M = \frac{w\ell^2}{10} \text{ (For ducts spanning over 3 or more supports)} \qquad \textbf{Eq. C-2}$$

where:

w = applied load (lbs/in)
ℓ = span between vertical supports (in)

The rectangular duct allowable span length for the typical case (for ducts spanning over 3 or more supports) is determined by:

$$\ell = \left[\frac{160\ F_b}{(2H + 2W)\ \rho\ K_1}\right]^{1/2} \qquad \textbf{Eq. C-3}$$

where:

- ρ = duct wall material density (lb/in^3). Note: an equivalent weight density should be used to account for additional material weight on the duct wall, such as joints and stiffeners.
- F_b = allowable material stress (psi)
- H = duct height (in)
- W = duct width (in)
- S_a = horizontal peak spectral acceleration (g's)
- S_v = vertical peak spectral acceleration (g's)
- R = (horizontal restraint span length)/(vertical support span length)
- K_1 = a derived constant (in^{-2}) based on a rectangular duct with a linear weight of $2\rho t(H+W)$, section moduli based on 2-inch by 2-inch angle sections at each corner, such that the section modulus about the horizontal is 8t[H-2+(2/H)] and the section modulus about the vertical is 8t[W-2+(2/W)], and an SRSS summation of seismic stresses, resulting in

$$K_1 = \left[\frac{S_a^2 R^4 W^2}{\left(W^2/2 - W + 1.0\right)^2} + \frac{S_v^2 H^2}{\left(H^2/2 - H + 1.0\right)^2}\right]^{1/2} + \frac{H}{\left(H^2/2 - H + 1.0\right)}$$

Note that the allowable span length equation is independent of duct thickness since duct section modulus and duct weight are both linear with respect to duct thickness.

For a given duct geometry, allowable span length screening charts can be developed using Eq. C-3 for various span ratios and spectral acceleration levels. Material allowable bending stress should be taken as defined in Section 4.2.1.

C.2 Circular Ducts

The evaluation guidelines (see Section 4) for circular duct support spacing define the duct section modulus to be:

$$Z = 0.25\pi D^2 t \qquad \textbf{Eq. C-4}$$

where:

- D = duct diameter (in)
- t = duct thickness (in)
- Z = duct section modulus (in^3)

The maximum bending moment is approximated by:

$$M = \frac{w\ell^2}{8} \text{ (For ducts spanning over one or two spans)} \qquad \textbf{Eq. C-5}$$

$$M = \frac{w\ell^2}{10} \text{ (For ducts spanning over 3 or more supports)} \qquad \textbf{Eq. C-6}$$

The design of duct support spacing for circular ducts is governed for small spans by duct bending. As the span length increases, buckling controls. Allowable stresses reflecting these modes of failure are given in Section 4.2.2.

The circular duct allowable span length for the typical case (for ducts spanning over 3 or more supports) is determined by:

$$L = \left[\frac{5\,F_b\,D}{2\,\rho\,K_2}\right]^{1/2} \qquad \textbf{Eq. C-7}$$

where:

ρ = duct wall material density (lb/in^3). Note: an equivalent weight density should be used to account for additional material weight on the duct wall, such as joints and stiffeners.
F_b = allowable material stress (psi)
S_a = horizontal peak spectral acceleration (g's)
S_v = vertical peak spectral acceleration (g's)
R = (horizontal restraint span length)/(vertical support span length)
D = duct diameter (in)
K_2 = a derived constant (lb/in^2) based on a circular duct with a linear weight of $\rho\,\pi\,D\,t$, a section modulus of $\pi\,D^2t/4$, and an SRSS summation of seismic stresses, resulting in

$$K_2 = 1 + (S_a^2R^4 + S_v^2)^{1/2}$$

For a given duct geometry, allowable span length screening charts can be developed using Eq. C-7.

C.3 Example Span Calculation

The following is an allowable span table for rectangular duct that was developed for the trial application by Southern Nuclear at Plant Hatch. The detailed calculation for the 20"x20" duct is shown following the calculation.

TURBINE BUILDING EL. 164'-0"
DWG. H-16050

Duct Height H (in)	Duct Width W (in)	Bottom of Duct El.	Duct Wall Gauge	Duct Wall Nom. Thickness (in)	Duct Wall Weight (lb/ft^2)	Trans. Stiffener Angle	Stiffener Angle Weight (lb/ft)	Stiffener Spacing (in)
10	22	178'-0"	22	0.0336	1.41	1x1x1/8	0.8	48
12	10	178'-6"	24	0.0276	1.16	none	N/A	N/A
		178'-6"						
18	24	178'-6"	22	0.0336	1.41	1x1x1/8	0.8	48
20	20	178'-6"	22	0.0336	1.41	1x1x1/8	0.8	48
34	40	178'-6"	20	0.0396	1.66	1x1x1/8	0.8	48
38	40	178'-6"	20	0.0396	1.66	1x1x1/8	0.8	48
40	40	178'-6"	20	0.0396	1.66	1x1x1/8	0.8	48
40	44	178'-6"	20	0.0396	1.66	1 3/8x1/8	1.1	24

Duct Height H (in)	Duct Width W (in)	Stiffener Weight (lb/in of duct)	Est. Weight of Joints (lb)	Trans. Joint Spacing (ft)	Est. Wt. of Joints (lb/in of duct)	Total Duct Weight (lb/in)	Duct Density p (lb/in^3)
10	22	0.092	4	8	0.042	0.760	0.353
12	10	0.000	4	8	0.042	0.396	0.326
18	24	0.119	4	8	0.042	0.984	0.349
20	20	0.114	6	8	0.063	0.960	0.35704
34	40	0.208	10	8	0.104	2.019	0.344
38	40	0.219	11	8	0.115	2.132	0.345
40	40	0.225	11	8	0.115	2.184	0.345
40	44	0.649	14	8	0.146	2.732	0.411

$S_a = 0.85$ $S_v = 0.33$

Duct Height H (in)	Duct Width W (in)	Derived Constant K_1 (in^{-2}) R=1.0	Derived Constant K_1 (in^{-2}) R=2.0	Derived Constant K_1 (in^{-2}) R=3.0	Derived Constant K_1 (in^{-2}) R=4.0	Derived Constant K_1 (in^{-2}) R=5.0	Derived Constant K_1 (in^{-2}) R=6.0	Derived Constant K_1 (in^{-2}) R=10.0
10	22	0.3607	0.5918	1.0097	1.6093	2.3608	3.2911	8.7058
12	10	0.4140	1.0285	2.0637	3.5142	5.3801	7.6604	20.9285
18	24	0.2113	0.4348	0.8182	1.3570	2.0491	2.8958	7.8224
20	20	0.2112	0.4880	0.9566	1.6137	2.4588	3.4919	9.5028
34	40	0.1116	0.2423	0.4650	0.7776	1.1795	1.6709	4.5302
38	40	0.1038	0.2351	0.4580	0.7706	1.1726	1.6640	4.5233
40	40	0.1005	0.2321	0.4550	0.7676	1.1696	1.6611	4.5204
40	44	0.0966	0.2152	0.4169	0.6998	1.0635	1.5082	4.0958

ALLOWABLE SPAN BETWEEN VERTICAL SUPPORTS (FT)

Duct Height H (in)	Duct Width W (in)	Duct Weight (lb/ft)	**R=1.0**	**R=2.0**	**R=3.0**	**R=4.0**	**R=5.0**	**R=6.0**	**R=10.0**
10	22	9.1	43	34	26	20	17	14	9
12	10	4.8	50	32	23	17	14	12	7
18	24	11.8	49	34	25	20	16	13	8
20	20	11.5	50	33	24	18	15	12	7
34	40	24.2	52	35	25	20	16	13	8
38	40	25.6	52	35	25	19	15	13	8
40	40	26.2	52	34	25	19	15	13	8
40	44	32.8	48	32	23	18	14	12	7

The detailed calculation for the 20"x20" duct in the tables above is shown below.

EXAMPLE CALCULATION FOR ALLOWABLE SPAN LENGTH:

Sample Calculation for 20" x 20" Rectangular Duct at Turbine Building Elevation 164:

Determine the duct wall equivalent weight density, *including an allowance for joints and stiffeners.* The duct material gauge, stiffener size, stiffener locations, and transverse joint locations are taken from the HVAC specification. [For purposes of clarity in this example, "1/2 SME" (the applicable Plant Hatch eathquake loading) has been changed to "SSE".]

$wt_{22} := 1.41 \cdot \frac{lb}{ft^2}$ — *From the spec., Section 9.8.1, duct material* is 22 gauge for 20" duct height and width. Material weight per square foot is from SMACNA Table 3-3.

$t_{nom\_22} := 0.0336 \cdot in$ — Nominal thickness of 22 gauge material, SMACNA Table 3-3.

$$\rho_{duct} := \frac{wt_{22}}{t_{nom\_22}}$$

$\rho_{duct} = 0.29 \frac{lb}{in^3}$ — Weight density of duct wall material only.

$H := 20 \cdot in$ — Duct height (vertical direction).

$W := 20 \cdot in$ — Duct width (horizontal direction)

$$Wt_{duct\_per\_in} := 2 \cdot \rho_{duct} \cdot t_{nom\_22} \cdot (H + W)$$

$Wt_{duct\_per\_in} = 0.783 \frac{lb}{in}$ — Weight of duct wall material only per inch of duct.

$Wt_{1x1x1\_8} := 0.8 \cdot \frac{lb}{ft}$ — Transverse joint stiffener for a 20" x 20" duct is one 1 x 1 x 1/8 angle bracing 4 ft. from joint (spec, Section 9.8.3b). Angle weight from AISC Manual.

$W_{duct\_stiffener} := Wt_{1x1x1\_8} \cdot [[2 \cdot (H + 2 \cdot in)] + (2 \cdot W)]$

$W_{duct\_stiffener} = 5.6\,lb$ Total weight of stiffener.

$S_{stiffener} := 4 \cdot ft$ Stiffener spacing (spec, Sect. 9.8.3b).

$$W_{stiff\_per\_in} := \frac{W_{duct\_stiffener}}{S_{stiffener}}$$

$$W_{stiff\_per\_in} = 0.12 \frac{lb}{in}$$

$W_{joint} := 6 \cdot lb$

$S_{joint} := 8 \cdot ft$

Transverse joints are 1 inch pocket slip or 1 inch bar slip on 8-ft centers (spec, Sect. 9.8.3b). Assumed additional weight of joints, including long. seam.

$$W_{joint\_per\_in} := \frac{W_{joint}}{S_{joint}}$$

$$W_{joint\_per\_in} = 0.06 \frac{lb}{in}$$

Weight allowance for joints per inch.

$$\rho := \frac{Wt_{duct\_per\_in} + W_{stiff\_per\_in} + W_{joint\_per\_in}}{2 \cdot t_{nom\_22} \cdot (H + W)}$$

$$\rho = 0.358 \frac{lb}{in^3}$$

Duct wall material density for a 20" x 20" duct, including allowance for joints and stiffeners.

Determine the allowable span, L, between vertical supports.

$F_b := 8000psi$ Normal allowable bending stress for galvanized sheet from Section 4.2.1.

$F_{b\_SSE} := 1.7 \cdot F_b$

$F_{b\_SSE} = 13600\,psi$

Increase allowable for the Hatch SSE earthquake per Section 4.2.1. This assumes the transverse joints are equivalent to SMACNA types T-1 through T-3 and T-15 through T-24 joints.

$\rho = 0.358 \frac{lb}{in^3}$ — Duct wall material density calculated above.

$H := 20 \qquad W := 20$ — Duct height and width (dimensionless).

$S_a := A_{H\_TB5\_7\%}$ — Applicable accelerations are from Turbine Building Mass Point 5 at El. 209'-0".

$S_a = 0.85\,g \qquad g := 1.0$

$S_v := A_{V\_TB5\_7\%}$

$S_v = 0.33\,g$

Let $R := 4.0$, Find L_{allow}

$$K_1 := \left[\frac{S_a^{\,2} \cdot R^4 \cdot W^2}{\left(\frac{W^2}{2} - W + 1.0\right)^2} + \frac{S_v^{\,2} \cdot H^2}{\left(\frac{H^2}{2} - H + 1.0\right)^2}\right]^{\frac{1}{2}} + \frac{H}{\left(\frac{H^2}{2} - H + 1.0\right)}$$

$$K_1 = 1.6137 \frac{1}{in^2}$$

$$L_{allow} := \left[\frac{160 \cdot F_{b\_SSE}}{(2 \cdot H \cdot in + 2 \cdot W \cdot in) \cdot \rho \cdot K_1}\right]^{\frac{1}{2}}$$

$$L_{allow} = 18.1\,ft$$

$L_{max} := 15\ ft$ — Maximum span between vertical supports for SSE earthquake, R=4.0

Check this value by calculating duct stresses using Section 4 of Reference 8. Calculate duct section modulus using 2-inch by 2-inch region at the four corners of the duct. Calculate section modulus consistent with Reference 8 Secion C.1 (treating the corner angles as a line and approximating the moment of inertia as equal to the sum of the Ad ^{2} terms).

$H := 20 \cdot in \qquad W := 20 \cdot in$

$t_{nom\_22} = 0.0336\,in \qquad L_{allow} = 18.1\,ft$

$$S_x := (8in) \cdot (t_{nom\_22}) \cdot \left(H - 2 \cdot in + \frac{2 \cdot in^2}{H} \right)$$

Calculate section modulus.

$$S_x = 4.865 \, in^3$$

Section modulus about the horizontal.

$$S_y := (8 \cdot in) \cdot (t_{nom\_22}) \cdot \left(W - 2 \cdot in + \frac{2 \cdot in^2}{W} \right)$$

$$S_y = 4.865 \, in^3$$

Section modulus about the vertical.

$$w := Wt_{duct\_per\_in} + W_{stiff\_per\_in} + W_{joint\_per\_in}$$

$$w = 0.96 \, \frac{lb}{in}$$

$$M_{x\_DL} := \frac{w \cdot L_{allow}^2}{10}$$

$$M_{x\_DL} = 378 \, lb \, ft$$

Dead load moment.

$$M_{x\_SSE} := \frac{(w) \cdot (S_v) \cdot L_{allow}^2}{10}$$

$$M_{x\_SSE} = 125 \, lb \, ft$$

Moment about the horizontal axis due to SSE earthquake.

$$M_{y\_SSE} := \frac{(w) \cdot (S_a) \cdot (L_{allow} \cdot R)^2}{10}$$

$$M_{y\_SSE} = 5135 \, lb \, ft$$

Moment about the vertical axis due to SSE earthquake.

$$f_{DL} := \frac{M_{x\_DL}}{S_x}$$

$$f_{DL} = 931 \, psi$$

Dead load stress.

$$f_{x\_SSE} := \frac{M_{x\_SSE}}{S_x}$$

$f_{x\_SSE} = 307 \text{ psi}$ Stress due to vertical earthquake.

$$f_{y\_SSE} := \frac{M_{y\_SSE}}{S_y}$$

$f_{y\_SSE} = 12665 \text{ psi}$ Stress due to horizontal earthquake.

Combining stresses per Section 4.1:

$$f_{total} := \left[\left(f_{x\_SSE}\right)^2 + \left(f_{y\_SSE}\right)^2\right]^{\frac{1}{2}} + f_{DL}$$

$f_{total} = 13600 \text{ psi}$ OK, this equals the allowable stress of 1.7 times 8000 psi (13,600 psi).

Allowable span based on stress is 18.1 feet, but 15 foot maximum span controls.

D

SEISMIC AND PRESSURE TESTING OF HVAC DUCTS

D.1 Introduction

Several tests were conducted by testing facilities to demonstrate the inherent resistance of HVAC systems to seismic damage in combination with pressure loadings. The test pressure loading (both positive and negative pressure) was generally several times the typical normal operating pressures in the ducts at nuclear power plants. Similarly, the seismic test loading, in the form of biaxial input motions or equivalent static loadings, was greater or equivalent to the maximum seismic demand at most nuclear power plants. The tests confirmed that the HVAC ducts constructed to SMACNA standards have adequate structural integrity and functional capability for the postulated DBE loads, as well as the normal operating pressure loads.

D.2 HVAC Duct Test Programs

D.2.1 Summary of Tests Performed for TVA Ducts

Vibration testing of rectangular ducts, which included both pocket lock and companion angle duct constructions, was conducted. Three different duct sizes (60"x24", 48"x18", and 36"x24") with width-thickness ratios ranging between 602 and 1671, and constructed to SMACNA standards, were tested. Four specimens of each duct size were available for testing for a total of twelve test specimens (six ducts with pocket locks and six ducts with companion angles). Each duct size was tested, non-concurrently, in the two directions perpendicular to the longitudinal axis of the duct specimen. The sheet metal thickness ranged from 20 ga. to 22 ga., and the duct span lengths varied from 14 to 28 feet. In order to tune the test setups to a first mode resonance of 8 to 11 Hz., which was the frequency range of the dominant response as defined by the required response spectra (RRS) with a peak acceleration value of 6.4g, a variable support was designed to alter the structural response of the duct/support system.

The tests demonstrated that both types of duct construction were capable of sustaining seismic loads of up to 6.4g with no or very little damage. The companion angle ducts experienced minor, highly localized failures in the duct skin that occurred as small separations in the duct skin corners or near a stiffener. These localized separations remained sufficiently closed that air delivery would not be significantly impaired. Ducts with pocket lock construction demonstrated an unexpected capability for sustaining high dynamic loads. The more flexible joints and higher damping in this type of construction are the primary reasons that no local failures, such as found with the companion angle ducts, were observed with the pocket lock construction.

The average damping values obtained from testing for companion angle and pocket lock ducts were about 7% and 10%, respectively. In addition, first mode natural frequency of each duct specimen was determined during testing. These tests revealed that the fundamental mode frequency of both pocket lock and companion angle ducts was less than what would be predicted based on beam theory and using the SMACNA four corner method to calculate the effective moment of inertia of the duct section. The resulting reduction factors used to adjust calculated natural frequencies are 0.59 and 0.87 for pocket lock and companion angle constructions, respectively.

All duct specimens were subsequently tested to failure. The peak acceleration values of actual test response spectra (TRS) at failure ranged from 10.2g to 14.0g for the companion angle ducts, and from 11.0g to 16.2g for the pocket lock ducts. Analysis of the test results, using the acceleration levels sustained at failure, indicated a bending stress at failure ranging from 25.2 to 51.7 ksi calculated by the SMACNA four corner effective section method. The general failure mode for companion angle ducts was a gradual, very ductile failure, with no complete separation of sections and with no gross opening of the pressure boundary. The general failure mode for pocket lock ducts was usually a sudden opening of the crimped joint. A sudden, catastrophic type of failure resulted and actual separation of duct sections caused the span to fall to the test table. It is noted that two of the pocket lock ducts could not be failed due to force limitations of the shake table.

D.2.2 Summary of Tests Performed for Limerick Ducts

The test program for ducts at Limerick consisted of testing seventeen test groups. Each test group consisted of three identical specimens except for one test group which had one specimen. Fifteen test groups included rectangular ducts with sizes ranging from 24"x24" to 96"x48". All duct specimens were of welded construction with a minimum sheet thickness of 18 ga., and the actual width-thickness ratios varied from 502 to 1605. Stiffener angle sizes ranged from 1"x1"x1/8" to 3"x3"x1/4", with spacing ranging from 24" to 48".

All specimens were tested for negative pressure with the exception of one specimen that was tested for positive pressure. The average negative test pressure ranged from 17.8 to 104.2 inches of water gage and the positive test pressure was 48.0 inches of water gage. Duct spans were from 8 to 12 feet long, and all duct specimen were simply-supported on the ends along the bottom end stiffener widths with the exception of two specimens that were supported along their end vertical stiffeners mounted on the height of the ducts.

All ducts were subjected to live load or seismic load simulation tests, or both, followed by the pressure test to failure or to a maximum negative pressure of 14 psi (-407.0" w.g.). Application of live load and simulated seismic load was accomplished by predetermined steel weights and bagged sand. Test internal pressures (negative or positive pressures) were applied to the specimen by an electrical pump connected in series with an accumulator tank. Only ducts in two groups were subjected to simulated seismic loading. The test sequence began with the live load tests followed by the seismic load tests, if any. Thereafter, the pressure tests to failure began. None of the ducts failed during the live load or seismic load tests. All ducts failed during the pressure load testing, with exception of the 8" diameter duct that did not fail.

In general, the test results demonstrated that failure modes of ducts were not catastrophic and there was significant reserve strength after failure. The negative pressure loading was the most important loading, since the failure mode under positive pressure was stiffener buckling whereas under negative pressure loading the duct failure mode was either the stiffener buckling or the corner crippling of the sheet metal. Dead load, live load, and seismic stresses in duct acting as a beam between supports were relatively low. The test results also supported using duct width-thickness and height-thickness ratios of up to 1500, as opposed to 500 and 200, respectively, per American Iron and Steel Institute (AISI) requirements.

D.2.3 Tests Performed at Other Plants

Similar duct tests were also conducted for CPSES and CP&L plants to verify the structural integrity of ductwork, particularly with longitudinal seam construction, under combined seismic and pressure (both positive and negative) loadings. The results of these tests are generally in agreement with the duct tests described in detail above.

D.3 Conclusions From Test Programs

In general, the tested ducts were either constructed to the SMACNA standards or were of a less conservative construction. The tests, collectively, provided the following results:

- The duct beam properties established based on the test results are comparable to the method prescribed by SMACNA guidelines but are less conservative.
- The average damping values for companion angle and pocket lock construction were established to be about 7% and 10%, respectively.
- Long spans of ducts (14' to 28') performed adequately under seismic input motions with a peak acceleration value of up to 6.4g.
- When tested to failure, with seismic input motion peak acceleration values ranging from 10.2g to 16.2g, failure of the duct specimens was very gradual and of a ductile nature, except for the ducts with pocket lock construction in which the crimped joints would suddenly open and cause a catastrophic type failure.

The overall conclusion from these limited tests indicates that as long as brittle failure of duct section connections is precluded, duct deformation under increasing loads is very ductile. Furthermore, for HVAC ducts with typical span lengths of about 15 feet and constructed to the SMACNA standards, duct capacity can be expected to significantly exceed typical demand under the combined normal operating and seismic loadings postulated for most nuclear power plants.

D.4 References

D-1. Neely, B. B., Warrix, L, "A Qualification and Verification/Improvement Test Program for HVAC Ducts Used in Nuclear Power Plants," presented at Century 2 Pressure Vessels and Piping Conference, August 1980.

D-2. Neely, B. B., Warrix, L., "A Procedure for Seismically-Qualifying HVAC Ducts Used in Nuclear Power Plants," presented at Second ASCE Conference on Civil Engineering and Nuclear Power, September 1980.

D-3. Desai, S. C., K. P. Buchert, and E. A. Marcinkevich, "Structural Testing of Seismic Category I HVAC Duct Specimens," Second ASCE Conference on Civil Engineering and Nuclear Power, Volume I., Knoxville, TN, September 1980.

D-4. Dizon, J. O., E. J. Frevold, and P. D. Osborne, "Seismic Qualification of Safety Related HVAC Duct Systems and Supports," 1993 ASME Pressure Vessel and Piping Division Conference, Denver, Colorado, July 1993.

E
ROD FATIGUE EVALUATION GUIDELINES

E.1 Introduction

Shake table tests have shown that the seismic capacity of fixed-end rod hanger trapeze supports is limited by the fatigue life of the hanger rods. Rod hanger trapeze supports should be evaluated for possible fatigue effects if they are constructed with fixed-end connection details.

Fixed-end connection details include double-nutted rod ends at connections to flanges of steel members, rods threaded into shell-type concrete expansion anchors and rods connected by rod coupler nuts to non-shell concrete expansion anchors. Fixed-end connection details also include rods with lock nuts at cast-in-place light metal strut channels and rod coupler nuts welded to overhead steel.

This attachment describes a screening method for evaluating rod hangers for fatigue based on the use of rod fatigue bounding spectra (shown in Figure E-1) and generic rod fatigue evaluation screening charts (shown in Figure E-2 through E-6).

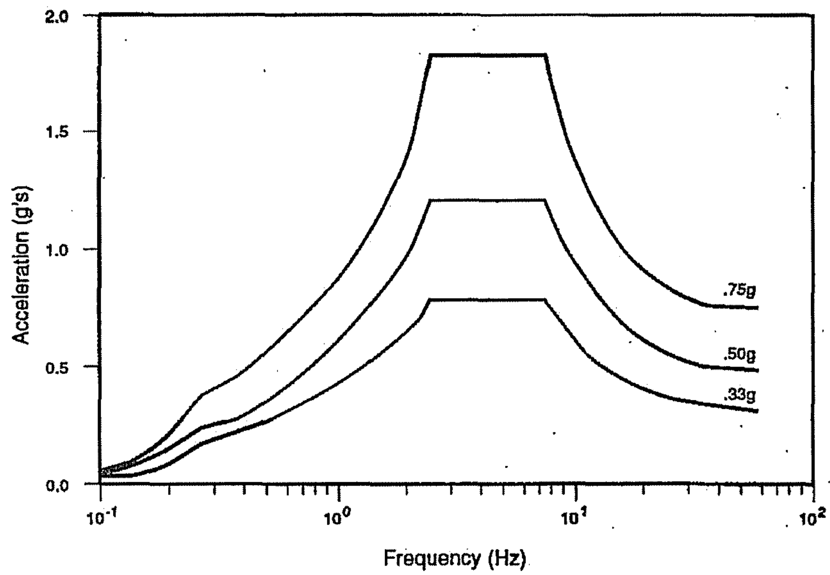


Figure E-1
Bounding Rod Fatigue Spectra

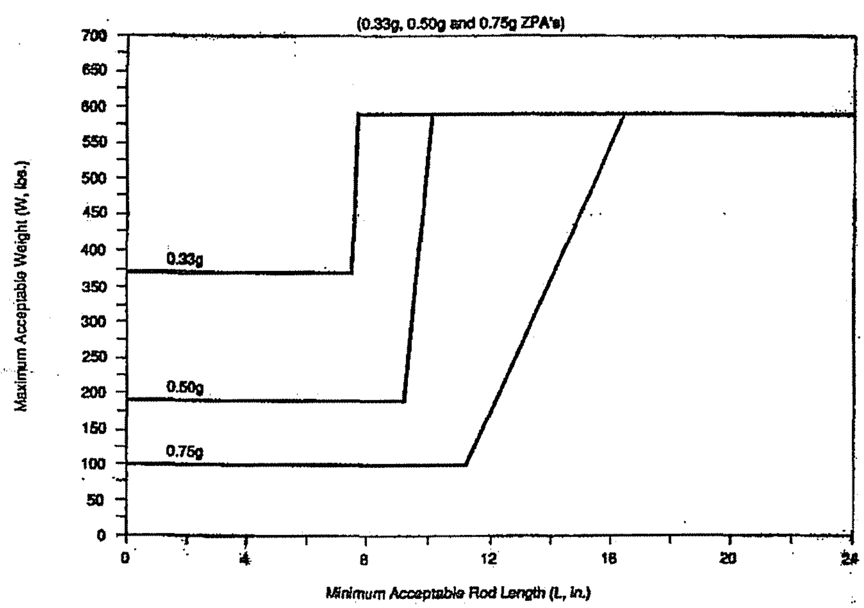


Figure E-2
Fatigue Elevation Screening Chart for ¼ inch Diameter Manufactured All-thread Rods. Weight Corresponds to the Total Supported Load (i.e., on both Rods). Length Corresponds to Clear Length

The screening charts are directly applicable to hangers constructed of manufactured all-thread rods in overhead suspended system runs with uniform length hangers. The charts may also be used for evaluation of supports constructed of field threaded rods and for short, isolated fixed-end rod hangers in more flexible systems with relatively much longer rod hangers; guidance is given later in this appendix on how to adjust the parameters when evaluating these special cases.

A fatigue evaluation should be conducted for rod hanger supports that have rods with fixed end connection details. For rod hung HVAC duct systems with rods of uniform length, the fatigue evaluation is conducted as follows:

1. Obtain the 5% damped floor response spectrum for the location of the support attachment point.

2. Compare the Bounding Rod Fatigue Spectra of Figure E-1 with the damped floor response spectra. For a given ZPA, if a Rod Fatigue Spectrum entirely envelops the floor response spectrum, proceed to step (c). If the Rod Fatigue Spectrum does not entirely envelop the floor response spectrum, then compare the Rod Fatigue Spectrum with the floor response spectrum (unbroadened) at the frequency of the support. Support frequency may be estimated as follows:

$$f_s = \frac{1}{2\pi}\sqrt{\frac{K_s}{M_s}}$$

where:

M_s	=	W_{equiv}/g (lbs-sec^2/in)
K_s	=	$24EI/L^3 + W_{equiv}/L$ (trapeze support, lbs/in)
W_{equiv}	=	total dead weight on the pair of rod supports (lbs)
g	=	gravitational constant (386.4 in/sec^2)
E	=	Young's modulus of rod hanger material (psi)
I	=	moment of inertia of rod root section (in^4)
L	=	length of rod above top tier (in)

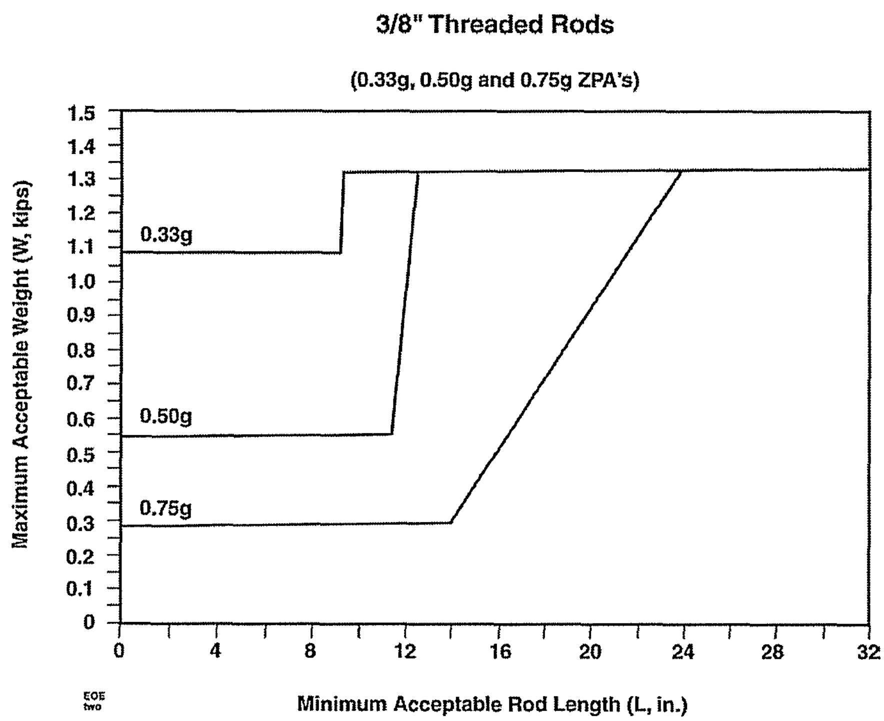


Figure E-3
Fatigue Evaluation Screening Chart for 3/8 inch Diameter Manufactured All-thread Rods. Weight Corresponds to the Total Supported Load (i.e., on both Rods). Weight Corresponds to Clear Length

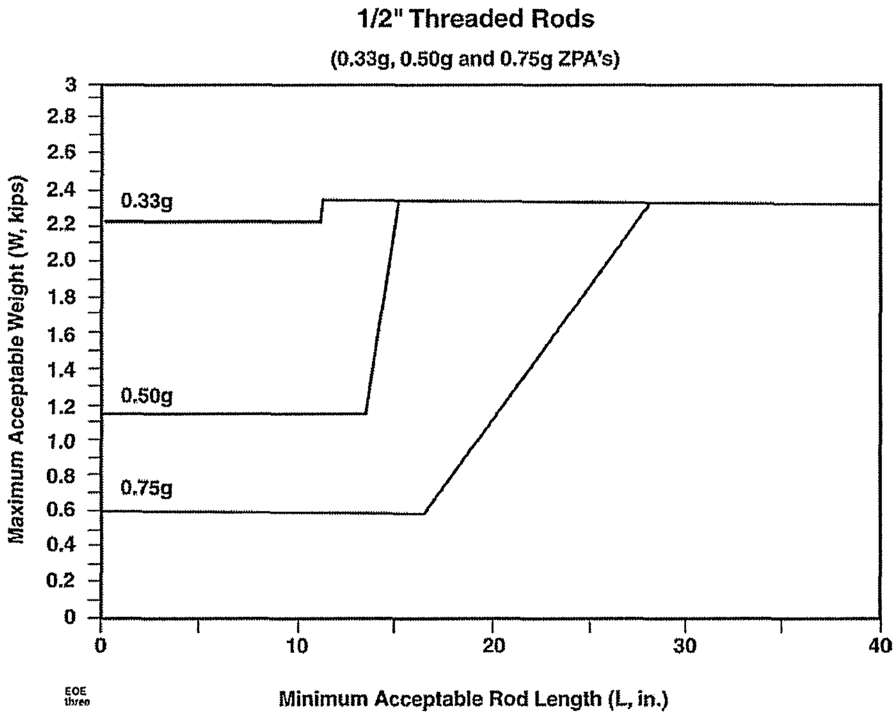


Figure E-4
Fatigue Evaluation Screening Chart for 1/2 - inch Diameter Manufactured All-thread Rods. Weight Corresponds to the Total Supported Load (i.e., on both Rods). Length Corresponds to Clear Length

If the bounding Rod Fatigue Spectrum does not envelop the floor response spectrum at the frequency of interest, then a more detailed evaluation should be conducted (by requirements other than the screening evaluation requirements presented herein).

1. Enter one of the Fatigue Evaluation Screening Charts shown in Figures E-2 through E-6 corresponding to the diameter of the threaded rod. Use the curve associated with the acceleration (0.33g, 0.50g or 0.75g) of the Rod Fatigue Bounding Spectrum of the previous step. If hanger length is greater than minimum acceptable length, and support dead weight is less than maximum acceptable weight, then the support is acceptable. This chart is applicable for all continuously threaded rods. For field threaded rods see (d) below.

2. If field threaded rods are to be evaluated, then the screening chart may be used for modified rod lengths and weights. For field threaded rods, double the weight and decrease rod length by 1/3 before using the chart.

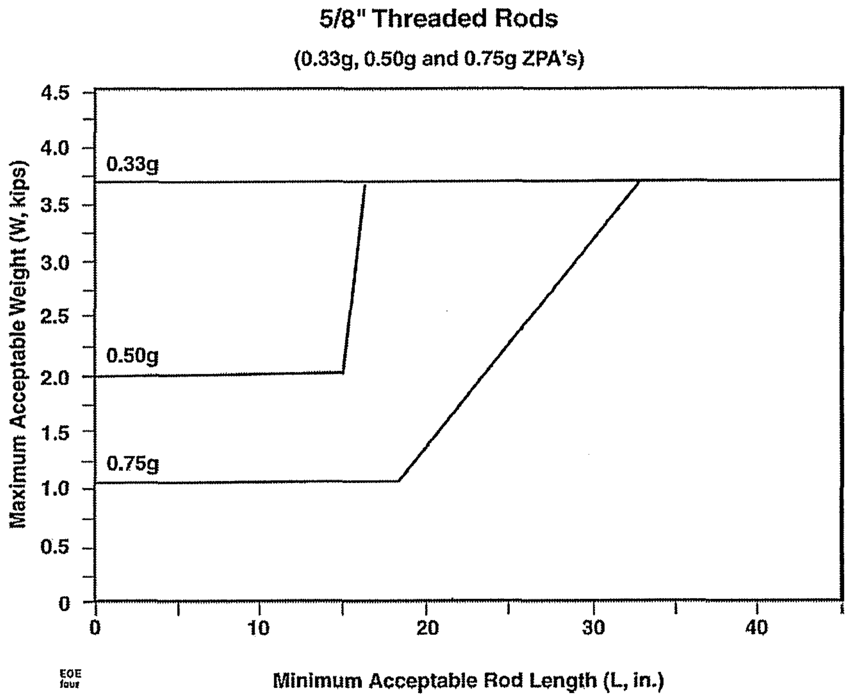


Figure E-5
Fatigue Evaluation Screening Chart for 5/8-inch Diameter Manufactured All-thread Rods. Weight Corresponds to the Total Supported Load (i.e., on both Rods). Length Corresponds to Clear Length

If isolated, short fixed-end rod hangers are used in a system with predominantly longer, more flexible hangers, a special evaluation should be conducted that decouples the response effects of the short isolated rod. The special evaluation proceeds as follows:

1. Estimate the frequency of the system, neglecting the isolated, short rod support. The frequency estimation formula given above may be used, providing that the length of the longer rods is considered.

2. Assure that the rod fatigue bounding spectrum envelops the applicable floor. response spectrum at this frequency of interest.

3. Back-calculate an equivalent weight for the evaluation of an isolated short rod, using the frequency of the long rods as follows:

$$W_{equiv} = \frac{24EIg}{(2\pi f_s)^2 L^3 - gL^2} \qquad \text{(trapeze support)}$$

4. Enter the appropriate Fatigue Evaluation Screening Chart (Figures E-2 to E-6) by using the above calculated equivalent weight and length of the isolated short rod hanger. If these parameters are in an acceptable region on the Fatigue Evaluation Screening Chart, then the isolated, short, fixed-end rod hanger is seismically adequate.

When using the charts, the simple equations given in this section for calculating response frequency should be used for consistency since these are the same equations used to generate the screening charts (that is, the screening charts are based on the simplified results obtained from detailed fatigue analysis, considering capacities determined by component test results).

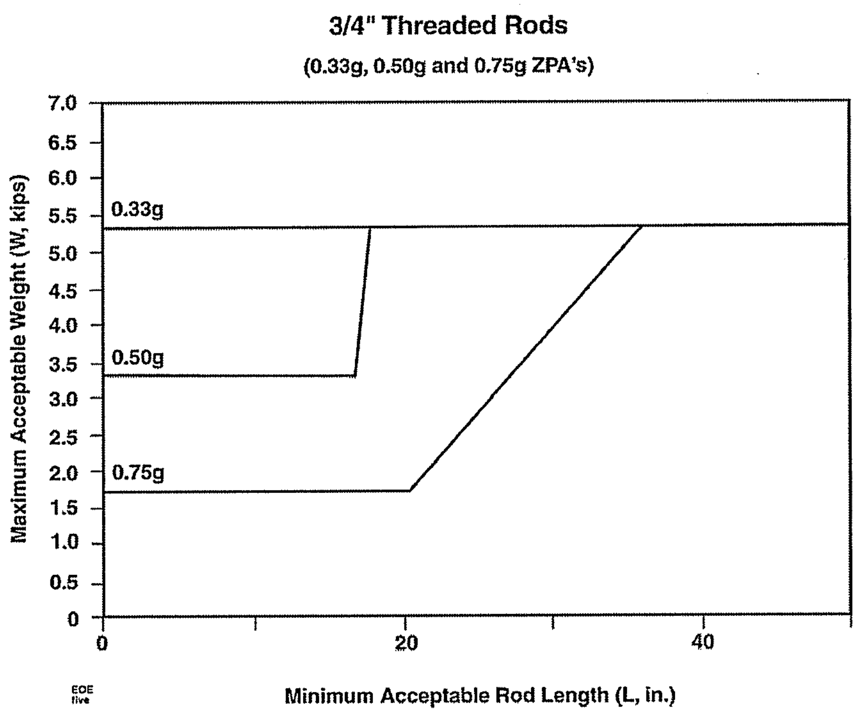


Figure E-6
Fatigue Evaluation Screening Chart for 3/4-inch Diameter Manufactured All-thread Rods. Weight Corresponds to the Total Supported Load (i.e., on both Rods). Length Corresponds to Clear Length

F

GUIDELINES FOR LIMITED ANALYTICAL REVIEW OF SUPPORTS

F.1 Introduction

A Limited Analytical Review (LAR) should be performed to assess the structural integrity of HVAC duct supports chosen as representative, worst-case bounding samples of the evaluation scope of HVAC duct systems. The purpose of the LAR is not to estimate actual seismic response and system performance during a DBE. Rather, the LAR is intended to demonstrate that the HVAC duct supports are at least as rugged as supports that performed well as evidenced by past experience, using empirical methods, plastic design principles, and engineering judgment.

There are several steps in the LAR process that must be understood in their entirety in order to ensure that the intent of the evaluation guidelines is met. These steps include the following checks, applying to both the support structural framing and the anchorage to the building structure:

- Dead load check
- Vertical capacity check
- Ductility review
- Lateral and longitudinal load check
- Rod hanger fatigue evaluations

The above checks are described in detail in the following sections except for the rod hanger fatigue evaluation. Guidelines for rod hanger fatigue evaluation are contained in Appendix E.

The first check to be performed is a standard, dead load design check. Supports not passing this check are outliers. This check serves the functions of an inclusion rule. Most of the earthquake experience database supports are conservatively assumed to have been adequately designed for dead weight. Adequate dead load design is thus the first important step for verification of seismic adequacy. This check is discussed in Section F.2.

The second check is the vertical capacity check. This check ensures high capacity of anchorage and primary anchor connections for the support, using simple calculational methods. Position retention is considered the most important aspect of ensuring structural integrity. This check is described in Section F.3.

The third check is a ductility review. This requires an assessment of how the support responds to lateral and longitudinal seismic motion, and what are the weak links in the support load path. The next two checks are the lateral and longitudinal load checks. These checks are static coefficient approaches for evaluating support capacity. If failure modes are ductile, then the lateral and longitudinal checks may not be required. See section F.4 for a discussion of the ductility review, and section F.5 for the lateral and longitudinal checks.

It is important for the evaluator to understand the functional goals (following the DBE) for the HVAC duct system being reviewed. If the seismic evaluation is being performed solely to ensure structural integrity, then support flexibility and ductility principles may be used to their fullest extent. Conversely, if duct system pressure boundary integrity is of high concern, then the evaluator must use caution when applying the ductility guidelines contained herein.

When ductile, plastic deformation of supports is allowed in either the lateral or longitudinal directions of motion, judgment *must* be passed on the potential consequences of this support behavior on the duct system. For example, consider an axial run of duct with an elbow at the end to a transverse run. If, in the longitudinal direction for the axial run, the supports are allowed to go into ductile plastic deformation, then the evaluator must ensure that the first lateral support around the elbow to the transverse run will respond in a similar manner. If not, the support may act as a hard spot, and cause potentially detrimental consequences to the duct elbow or that first lateral support on the transverse run (see Figure F-1).

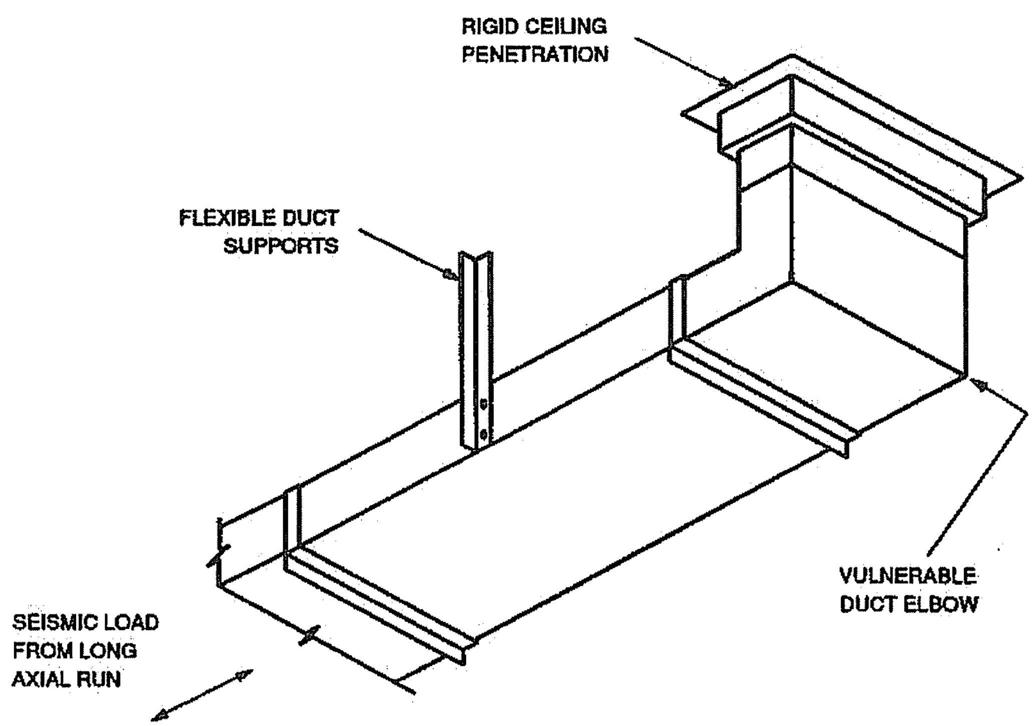


Figure F-1
Vulnerable Duct Elbow Adjacent to Rigid Lateral Restraint

F.2 Dead Load Check

A detailed dead load design review of the representative worst-case bounding sample HVAC duct supports should be conducted using normal design working stress allowable loads. The check should consider the as-installed configuration, connection detailing, and loading condition of the support. All components such as bracket and trapeze cross members, vertical support members, internal framing connections, and support anchorage should be checked. All system eccentricities, including load to anchor point eccentricity, should be considered. Evaluation of clip angle bending stresses may be excluded for trapeze supports suspended from the overhead. Loads from other attached systems, such as piping or conduit, should be considered.

Consideration should also be given to the seismic adequacy of the wall to which the HVAC duct supports are attached. Reinforced concrete structural walls are not a concern but masonry walls should be checked to verify that they are seismically adequate. Anchorage into transite walls (asbestos fiber board) and gypsum board partitions should be considered outliers. Reduced anchor bolt capacities should be used for expansion anchors in masonry block walls. The anchorage of partition walls and shielding walls should be checked.

F.3 Vertical Capacity Check

The check concentrates on the support anchorage, focusing on the weak link in the support anchorage load path. High vertical capacity is one of the primary design attributes that is given credit for good seismic performance. The Vertical Capacity Check evaluates whether the vertical capacity to dead load demand ratio is as least as high as that of support systems in the earthquake experience database that performed well. The high vertical capacity provides considerable margin for horizontal earthquake loading.

The Vertical Capacity Check is an equivalent static load check, in which the support is subjected to a vertical load, P_V, defined as

$$P_V = F_V \text{ (Dead Load)},$$

where F_V is a vertical load increase factor defined as

$$F_V = \text{Greater } [5.0g,\ 6.0\ (ZPA_h)].$$

ZPA_h is the zero period acceleration of the floor response spectrum at the support anchorage.

This check is limited to the HVAC duct support primary connections and anchorage. It is not necessary to evaluate clip angle bending stress or secondary support members. The lower support member of floor-to-ceiling configurations and base-mounted supports should be checked for buckling.

Eccentricities resulting in anchor prying and eccentricities between vertical support members and anchor points should, in general, be ignored. This concept is the result of back-analyses of earthquake experience database supports and is consistent with limit state conditions observed in test laboratories.

For cantilever bracket support types, the eccentricity of the cantilevered dead load should be ignored.

For trapeze frame and rod-hung supports, load distribution between the two vertical framing members should be considered only if the center of the load is significantly distant from the centerline of the support frame. The bending strength and stiffness of frame members should be checked for transfer of the load between anchor bolts when overhead support is provided by light metal framing with anchor bolts spaced at relatively large intervals and when multiple anchor bolts are needed to resist the vertical load.

For most HVAC duct support systems, the anchorage will be found to be the weak link in the load path. For these cases of HVAC duct supports the Vertical Capacity Check is simply a comparison of anchor capacity to F_v times the supported load.

If the Vertical Capacity Check is not met, then the support should be classified as an outlier.

F.4 Ductility Check

An evaluation should be conducted of the supports selected for review to characterize their response to lateral and longitudinal seismic motion as either ductile or potentially non-ductile. The purpose of the ductility check is to identify support configurations that require a lateral and longitudinal load check (discussed in Section F.5).

Supports suspended only from overhead may be characterized as ductile if they can respond to lateral seismic motion by swinging freely without degradation of primary vertical support connections and anchorage. Ductile, inelastic performance such as clip angle yielding or vertical support member yielding is acceptable so long as deformation does not lead to brittle or premature failure of overhead vertical support.

Review of typical HVAC duct support systems in the earthquake experience and shake table test databases indicates that many overhead mounted support types are inherently ductile for lateral seismic motion. Back-analysis of many database supports predicts yielding of members and connections. These database systems performed well, with no visible signs of distress. Ductile yielding of suspended supports results in a stable, damped swaying response mode. This is considered to be acceptable seismic response and use of the support plastic moment is permitted.

The ductility review of anchorage connection details is most important for rigid-type suspended supports. Supports with rigid, non-ductile anchorage that do not have the capacity to develop the plastic strength of the vertical support members can possibly behave in a non-ductile fashion.

Examples include large tube steel supports welded to overhead steel with relatively light welds, or rigid supports welded to large base plates and outfitted with relatively light anchorage. These types of support systems are not well represented in the database and are not preferable since they have a brittle failure mode.

The seismic design of certain HVAC duct support members may have been controlled by high frequency requirements rather than design loads, yet anchors may have been sized by the design loads. These types of supports may have low seismic margin due to loads placed on the support which were not considered by the original design. Supports with rigid, non-ductile anchorage are subject to further strength review (see Section F.5).

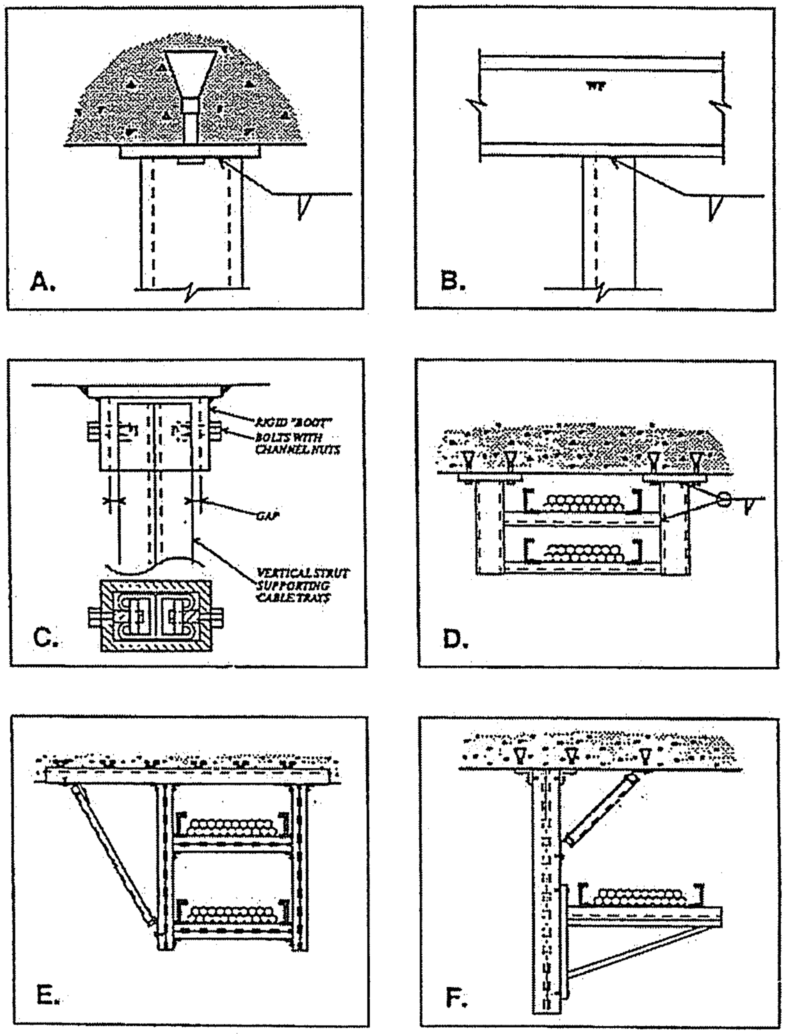
Examples of ductile and non-ductile support connection details and configurations are described below and illustrated in Figure F-2.

Standard Catalog Light Metal, Strut Framing Members, Clip Angles, and Bolts with Channel Nuts. Unbraced supports suspended from overhead, constructed of standard Catalog light metal, strut framing channels, clip angles, and bolts with channel nuts may be characterized as ductile. This includes supports constructed of standard catalog light metal strut framing gusseted, clip angle connections.

Welded Steel Members. If an anchor point connection weld is stronger than the vertical member, then a plastic hinge will be able to form in the vertical member, allowing ductile response without weld failure. A support is seismically rugged so long as overhead support is maintained. In this case, plastic hinge action in the vertical member prevents transmission of loads capable of failing the welded anchorage point. For open channel structural sections, an all-around fillet weld whose combined throat thicknesses exceed the thickness of the part fastened, may be considered capable of developing the plastic hinge capacity of an open channel section vertical member. If the plastic hinge capacity of the framing support member exceeds the capacity of the weld, then a brittle failure is possible, which is not acceptable seismic performance. For light metal, strut framing members, welded connections are likely to be non-ductile and thus not capable of developing plastic moment capacity of the framing member.

Ceiling Connection Plate Secured with Expansion Anchors. Supports with overhead anchorage provided by a plate attached to concrete with expansion anchors should be evaluated for ductility as follows. The anchorage may be characterized as ductile if it is stronger than the plastic flexural strength of the vertical support member. A simple anchor moment capacity estimate may be used, by multiplying the bolt pullout capacity times the distance between the bolts or center of bolt groups. In some cases, it may be possible to demonstrate ductility if the ceiling connection plate is the weak link in the anchorage load path. This is similar to the case of clip angle bending. The key to characterizing a support as ductile or non-ductile is reviewing the anchorage load path, and determining if the weak link responds in the ductile or brittle manner.

Braced Cantilever Bracket and Trapeze Frame Supports. The presence of a diagonal brace in a support has the potential of significantly increasing the pullout loads on anchorage when the support is subjected to horizontal motion. This is a function of the support geometric configuration, the realistic capacity of the brace, and the realistic capacity of the anchorage. Non-ductile behavior is possible when the brace reaction of horizontal load, plus dead load, has the capability of exceeding the primary support anchor capacity. If a brace buckles or has a connection failure before primary support anchor capacity is reached, then the support may be considered as ductile. Braced supports are subject to further horizontal load capability review with a focus on primary support anchorage.



Connections A and B are partially welded connection details. Partial welds cannot develop the plastic moment capacity of the vertical member, and are considered non-ductile.

Connection C is the non-ductile rigid boot connection.

Connection D is a rigid moment-resisting frame and should be checked for horizontal load.

Connections E and F are diagonally braced, and should be checked for horizontal load

Figure F-2
Examples of Potentially Non-Ductile Support Connection Details and Configurations

Unbraced Rigid Trapeze Frames. Trapeze frames constructed as moment-resisting frames, such as those with a number of stiff cross-beam members welded to the two vertical supports have the potential of significantly increasing the pullout loads on anchor bolts when the frame is subject to horizontal motion. Non-ductile behavior is possible when the rigid frame anchor point reactions to horizontal load exceed the anchor capacity. Unbraced rigid trapeze frames are subject to further horizontal load strength review with focus on anchorage.

Floor-mounted Supports. Plastic behavior of floor-mounted supports may lead to structural instability. Ductility, as defined by these guidelines, only applies to suspended systems. Floor-mounted supports are characterized as non-ductile, and are subject to further horizontal strength review with focus on stability.

Rod Hanger Trapeze Supports. Supports constructed of threaded steel rods with fixed-end connection details at the ends of the rods behave in a ductile manner under horizontal motion; however, relatively short rods may undergo very large strains due to bending imposed by horizontal seismic motion, at the fixed ends of the rods. Low cycle fatigue may govern response. Rod hanger trapeze supports with short, fixed-end rods should be evaluated for low cycle fatigue effects.

If a support is characterized as non-ductile or has questionable ductility, then its lateral load capacity should be verified, as discussed in Section F.5. If a support is characterized as ductile, and the duct system as a whole, depending on the functional goals, is judged capable of handling anticipated plastic deformation of supports, then it may be judged that no further lateral or longitudinal load check is necessary.

F.5 Lateral and Longitudinal Load Check

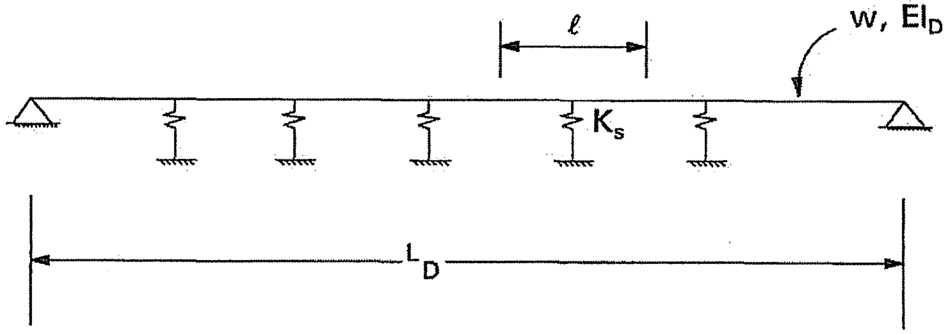
A Lateral and Longitudinal Load Check should be performed for the bounding case HVAC duct supports that are characterized as potentially non-ductile. The Lateral and Longitudinal Load Check is in the form of an equivalent static lateral load coefficient.

If a support is non-ductile or has questionable ductility, then it should be analyzed for dead load plus a transverse acceleration of 1.0 times the Peak Spectral Acceleration (PSA) of the in-structure response spectrum, at 5% damping, for the anchor point in the plant where the HVAC duct system is attached.

To evaluate a given support, transverse loads for the two horizontal axes should be applied, and capacities checked, non-concurrently. That is, two separate load cases should be checked. For example, one load case would be dead load plus loads due to north-south seismic motion, and the second would be dead load plus loads due to east-west seismic motion.

For these loading conditions, judgment must be used to ascertain the tributary mass, or length of duct run, to consider for each direction of load. As a general guideline, tributary length of duct for consideration for each direction of load should include one-half the length of duct to the next supports, on either side of the support being evaluated, that resist load in that direction. This general rule may not always apply, and tributary spans should be adjusted as judged necessary based on stiffness considerations for the duct systems.

It is not required that the PSA always be used; this is intended to be a "first screen" method. If a reasonably accurate estimate of dominant mode response can be made, then the spectral acceleration associated with the frequency estimate may be made. As appropriate, beam-on-elastic-foundation approximations or Dunkerley's equation approximations may be used (separately or together). These frequency estimation approaches are shown in Figures F-3 and F-4. When these methods are used, the basis for their applicability should be documented with the LAR calculations.



For I_D use SMACNA 2-inch corner section method. K_S and ℓ are typical.

$W_{equiv} = w\ell$

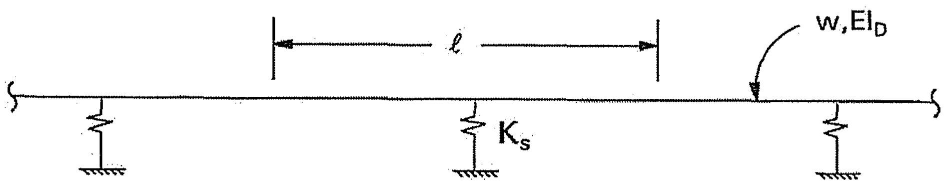
$f_S = (1/2\pi)(K_s\, g/W_{equiv})^{1/2}$

$f_D = (0.87)(\pi/2)(EI_D g/wL_D^4)^{1/2}$

0.87 is for companion angle duct. Use 0.59 for pocket lock.

$f_{system} = (f_s^2 + f_D^2)^{1/2}$

Figure F-3
System Frequency Estimation Using Beam-on-Elastic-Foundation Approximation



For I_D use SMACNA 2-inch corner section method. K_S and ℓ are typical

$W_{equiv} = w\ell$

$f_S = (1/2\pi)\,(K_s\, g/W_{equiv})^{1/2}$

$f_D = (0.87)(\pi/2)(EI_D g/w\ell^4)^{1/2}$

0.87 is for companion angle duct. Use 0.59 for pocket lock.

$f_{system} = [(1/f_S)^2 + (1/f_D)^2]^{-1/2}$

Figure F-4
Dunkerley's Equation Frequency Estimation Methodology

The simple equivalent static load coefficient method may be too conservative for very low frequency supports with long drops from the ceiling anchorage to the HVAC duct. The static coefficient method predicts very high connection bending moments in these cases. In this case, the bending moment imposed on the ceiling connection may be limited by peak seismic deflection and not seismic acceleration. An alternative loading condition of dead load plus reaction forces due to a realistic estimate for imposed seismic deflection may be used. Seismic deflection may be calculated by using floor spectral displacement at a lower bound frequency estimate, considering only single degree-of-freedom pendulum response of the support.

For diagonally-braced supports with ductile overhead anchorages, the load reaction imposed on the support anchorage during the Lateral Load Check does not need to exceed the buckling capacity of the brace or its connections. For diagonally-braced supports where the anchorage is not ductile, the portion of the lateral load that is not resisted by the brace should be redistributed as bending stress to the overhead connection. The loads in the diagonal brace will cause additional vertical and horizontal loads on the anchorage, and should be accounted for.

An upper and lower bound estimate should be used for buckling capacity of the brace, whichever is worse, for the overhead anchorage. There is considerable variation in test data capacity for light metal strut framing connections. An upper bound estimate of 2.0 times the manufacturer's suggested capacities can be used for these connection types.

G
PEER REVIEW COMMENTS

Peer Review Comments on EPRI Seismic Evaluation Guidelines for HVAC Duct and Damper Systems

R.P. Kennedy
February 7, 2004

1. Introduction

The EPRI Technical Report 1007896 entitled *Seismic Evaluation Guidelines for HVAC Duct and Damper Systems* (Ref. 1) provides an earthquake experience based approach for verifying the seismic adequacy of HVAC duct and damper systems. It is my understanding that Ref. 1 has not been subjected to a detailed review by an independent peer review panel in a manner similar to that performed for other classes of equipment evaluated using an earthquake experience based seismic evaluation approach. Although not from an independent peer review panel, this report presents my individual independent peer review of the seismic evaluation guidelines presented in Ref. 1.

The seismic evaluation approach recommended in Ref. 1 consists of a two-step process. The first step consists of a detailed in-plant seismic walkdown screening review of the HVAC duct systems to be evaluated. This review is to be conducted by a Seismic Review Team (SRT) that consists of at least two qualified engineers that must mutually agree that the walkdown reviewed HVAC duct system has passed the seismic screening so that it is eligible to have its seismic adequacy verified by the earthquake experience based approach. Guidance for this seismic walkdown review is presented in Section 3 of Ref. 1.

For the second step, the SRT selects a bounding sample of HVAC duct systems and supports to be subjected to a simplified analytical review. Details for this analytical review are presented in Section 4 of Ref. 1. The simplified analytical approach presented in Section 4 of Ref. 1 is very similar to the *Design-by-Rule* approach presented in Ref. 2 for HVAC duct systems and their supports. Ref. 2 was very thoroughly reviewed and accepted by an independent peer review panel.

The above summarized two-step process is also very similar to the earthquake experience based approach developed by SQUG and presented in Section 8 of Ref. 3 for Cable and Conduit Raceway Systems and their supports. Ref. 3 was also very thoroughly reviewed and accepted by an independent peer review panel.

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I served as chairman of the five member independent Senior Seismic Review and Advisory Panel (SSRAP) which provided considerable technical review and advice during the development of the SQUG (Ref. 3) approach for evaluating the seismic adequacy of 20 classes of equipment plus Cable and Conduit Raceway Systems and their supports. SSRAP (Ref. 4) unanimously endorsed the SQUG (Ref. 3) approach for use on existing components in existing nuclear power plants.

Furthermore, I served as a member of a four member independent panel established by the U.S. Nuclear Regulatory Commission to provide advice on the use of this earthquake experience based approach for the seismic qualification of new equipment, cable trays, and HVAC duct systems in new plants. In Chapter 5 of Ref. 5, this panel explicitly endorsed the earthquake experience based *Design-by-Rule* approach proposed in Ref. 2 for HVAC ducts and their supports. The independent panel stated:

> "The Panel fully supports the idea of 'design-by-rule' for HVAC ducts. This requires simplified design procedures with minor computational needs. The Panel observed that, in the past, significant efforts were expended for nuclear power plants to analyze and design HVAC ducts. The lessons learned from past practice and experience, if incorporated in the new design rules, will significantly reduce cost without sacrificing confidence in performance. Therefore, the Panel not only endorses a new design approach but also encourages it."

Therefore, even though the detailed material presented in Ref. 1 has not been reviewed by an independent peer review panel, the overall approach has been reviewed and endorsed by independent peer review panels.

My review of Ref. 1 has heavily concentrated upon whether important aspects of the SQUG approach (Ref. 3) for Cable Raceways and the *Design-by-Rule* approach (Ref. 2) for HVAC systems and their supports have not been incorporated into Ref. 1.

2. Overall Conclusions

In general, I find the seismic evaluation guidelines for HVAC Duct and Damper Systems and their supports presented in Ref. 1 to be excellent. However, I believe that Ref. 1 is deficient in certain details that are included in either Ref. 2 or 3. These minor deficiencies are discussed in the remainder of this report. I recommend that these minor deficiencies be corrected. Each minor deficiency can be easily corrected and will have very little overall impact on the use of Ref. 1.

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3. Minor Deficiencies in Ref. 1
3.1 Limits on Applicability

In Section 2.1 of Ref. 1, it is stated that the guidelines are applicable to any HVAC duct and damping system at any elevation in a plant where the nuclear plant free-field ground motion 5% damped seismic design spectrum does not exceed the Seismic Motion Bounding Spectrum of Ref. 1.

I do not consider this limit to be sufficient. HVAC duct systems can be supported at very high elevations in a variety of buildings where the in-structure-response-spectra (ISRS) can be much higher than the free-field ground motion. I don't believe that the experience data adequately covers this situation.

Section 3.1 of Ref. 2 restricts its proposed *Design-by-Rule* method to situations where the horizontal zero period acceleration (ZPA_h) at the HVAC support anchorage does not exceed 2.0g. I doubt that very many situations exist where ZPA_h exceeds 2.0g when the free-field spectrum is less than the Bounding Spectrum. Even so, I strongly believe that the ZPA_h less than 2.0g limit is an important additional limitation that should be included in Ref. 1. I doubt that it can be demonstrated that any of the HVAC duct earthquake experience data base included situations where ZPA_h exceeded 2.0g. Without a significant amount of such data, the 2.0g limitation is needed.

3.2 Duct Span Lengths Between Vertical Supports

Section 3.2.1 of Ref. 1 suggests that tables of allowable duct spans and maximum cantilever lengths for various duct sizes be developed prior to the seismic walkdown screening of duct systems. Development of these allowable span tables should be a prewalkdown requirement and not just a suggestion.

Section 3.2.1 refers to Appendix C as an example of how a tabulation of allowable spans can be developed. Here again, Appendix C should be a requirement and not just an example. Furthermore, it would be helpful to have an example application of Appendix C with an example set of screening tables for some realistic situation.

In addition, some upper limit on vertical support spans should be established. This limit should be based upon spans observed in the earthquake experience data base. Ref. 2 which was based on the experience data in Ref. 6 established the following limits on support spans for the *Design-by-Rule* method:

1. Duct support to support spans should not exceed 15 feet.

-3-

2. Supports should be provided within 5 feet from fittings such as Ts and Ys in each branch of the fitting

3. Duct cantilevered length (beyond end of last support) should not exceed 6 feet.

These limits are intended to place the duct spans within the limits of extensive earthquake experience data. Unless significant amounts of new earthquake experience data can be used to justify higher span limits, I believe that these limits from Ref. 2 should be incorporated into Ref. 1.

3.3 Seismic Interaction Review

Sections 3.4 of Ref. 1 requires that the SRT conduct a seismic interaction review. However, very little guidance is given in Ref. 1 for the Proximity Interaction review. A key element of this review is to estimate the seismic induced displacement of both the duct systems and of any adjacent item that might damage the duct upon impact. Some guidance on how to make these displacement estimates for the duct system should be included in Ref. 1. At least some limited guidance is presented in Section 3.3 of Ref. 2. This guidance could at least serve as a start for guidance in Ref. 1.

3.4 Vertical Capacity Check

Section 4.5.1 of Ref. 1 requires a Vertical Capacity check of the vertical supports. Further guidance is given in Appendix F. This check is to verify that the duct supports lie within the range of duct support capacities within the earthquake experience data base.

Section 4.5.1 deals only with the metal frame. Section 4.5.3 deals with anchorage. No Vertical Capacity check is required in Section 4.5.3. It needs to made very clear in Section 4.5 that the Vertical Capacity check applies both to the metal frame and the anchorage. Appendix F does properly include anchorage in this check. Even so, it should be made clear in Section 4.5.

The fourth paragraph on Page 4-14 of Section 4.5.1 states that it is permitted to exceed AISC allowable stresses in certain situations. However, it is my understanding that essentially all of the successful duct supports in the Ref. 6 earthquake experience data base passed the Vertical Capacity check at AISC allowable stress levels. For this reason, Section 6.1.2 of Ref. 2 requires that the Vertical Capacity check to be passed at AISC allowable stress levels. Unless it can be demonstrated that a significant number of the successful duct supports in the earthquake experience data do not pass the Vertical Capacity check at AISC allowable stress levels, I strongly recommend that the Vertical Capacity check be limited to the AISC allowable stresses.

Ref. 1 does not clearly delineate the limits of the Vertical check. For ductile failure modes, only primary stresses from vertical loads need to be included. Stresses relieved by small displacements do not have to be included in the Vertical Capacity check. Some useful guidance on this topic is given in Section 6.1.2 of Ref. 2.

The Vertical Capacity check is made for a vertical load P_V defined by:

$$P_V = F_V * (\text{Dead Load}) \tag{1}$$

where F_V is a vertical load increase factor defined in Ref. 1 by:

$$F_V = 5.0g \tag{2}$$

The independent peer review panel which reviewed Ref. 2 did not consider F_V from Eqn. (2) to be adequate for high seismic lateral forces. As a result Ref. 2 uses:

$$F_V = \text{Greater}[5.0g, 6.0(ZPA_h)] \tag{3}$$

where ZPA_h is the zero period acceleration at the support anchor. The net effect of this change is to increase F_V when ZPA_h exceeds 0.83g.

In my opinion, Ref. 1 should use Eqn. (3) to define F_V unless it can be demonstrated that a significant number of the successful duct supports in the data base will not pass the Vertical Capacity check when F_V from Eqn. (2) is replaced by F_V from Eqn. (3).

3.5 Peer Review Requirement

The earthquake experience based seismic evaluation approaches presented in Refs. 1 through 3 rely heavily on the judgment and experience of the SRT. This judgment and experience is used in lieu of extensive analyses. As a result, both the SSRAP report (Ref. 4) and the SQUG approach (Ref. 3) require independent peer review of the judgments and conclusions made by the SRT as well as a sampling review of the limited analytical evaluations.

However, Ref. 1 does not require this independent peer review. I consider this to be a fatal deficiency in Ref. 1 that must be corrected. Independent peer review is an integral part of an experience based approach.

4. Final Comments

I fully concur with and support the use of the Ref. 1 seismic evaluation guidelines for HVAC duct and damper systems and their supports so long as the minor deficiencies identified in Section 3 are corrected. In the meantime, I suggest that users of Ref. 1 should implement the changes recommended in Section 3 for their plant specific use. I don't believe that any of these changes will significantly affect the usefulness of Ref. 1.

References

1. EPRI, *Seismic Evaluation Guidelines for HVAC Duct and Damper Systems*, Technical Report 1007896, April 2003

2. ARC, *Advanced Light Water Reactor (ALWR) First-of-a-Kind-Engineering (FOAKE) Project on Design Concepts for HVAC Ducting and Supports*, April 1995

3. Seismic Qualification Utilities Group (SQUG), *Generic Implementation Procedure (GIP) for Seismic Verification of Nuclear Plant Equipment*, Revision 3A, December 2001

4. Senior Seismic Review Advisory Panel (SSRAP), *Use of Seismic Experience and Test Data to Show Ruggedness of Equipment in Nuclear Power Plants*, Sandia Report SAND92-0140, Part 1, 1992

5. Bandyopadhyay, K.K., Kana, D.D., Kennedy, R.P., and Schiff, A.J., *An Evaluation of Methodology for Seismic Qualification of Equipment, Cable Trays, and Ducts in ALWR Plants by Use of Experience Data*, NUREG/CR-6464, prepared for U.S Nuclear Regulatory Commission, July 1997

6. ARC, *Advanced Light Water Reactor (ALWR) First-of-a-Kind-Engineering (FOAKE) Project on the Performance of HVAC Ducts and Supports in Earthquakes and Tests*, April 1995

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