PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Development of an Electrical Substation Equipment Performance Database for Evaluation of Equipment Fragilities

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PEER 2001/06
APRIL 1999

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Final Report
April 1, 1999

Prepared for the Pacific Gas and Electric Company and for
the Pacific Earthquake Engineering Research Center

PEER Report 2001/06
Pacific Earthquake Engineering Research Center
College of Engineering
University of California, Berkeley
April 1999

EXECUTIVE SUMMARY

A database has been developed that documents the performance of substation equipment in 12 California earthquakes. The equipment in the database is owned by the Pacific Gas and Electric Company, the Los Angeles Department of Water and Power, Southern California Edison and the California Department of Water Resources. The majority of data relates to equipment operating at 220/230 kV and 500 kV. The database is organized into an Excel 5.0 spreadsheet with 68 data fields describing earthquake location, ground motion, site location and conditions, equipment characteristics, performance of equipment, failure mode, and restoration time. Each record represents a single piece of damaged equipment or several pieces of similar undamaged equipment.

Ground motions in the database are based on recordings if the site was instrumented. In other cases, ground motions are based on event-specific attenuation relationships developed by Somerville and Smith (1999).

The purpose of the database is to provide a basis for developing or improving equipment vulnerability functions. The probabilities of failure are calculated by dividing the number of damaged items by the total number of items of that type at each site. Using peak ground acceleration as the ground motion parameter, failure probabilities are compared with opinion-based fragility curves for a few selected equipment classes. Comparisons are somewhat crude in that the calculated failure probabilities do not include information about the mode of failure. The comparisons indicate that some of the existing fragility curves provide reasonable matches to the data and others should be modified to better reflect the data.

ACKNOWLEDGMENTS

I would like to thank Anshel Schiff for all of his help in transferring and explaining the initial equipment damage database and in providing additional support documentation for several published articles on substation equipment damage. Dennis Ostrom's insight into damage and inventory of Southern California substations was invaluable. Ed Matsuda, Eric Fujisaki, Robert White, Norman Abrahamson, and Woody Savage of Pacific Gas and Electric Company (PG&E) provided valuable guidance and data on equipment inventories, use, priorities, function, and damage. Paul Somerville and Nancy Smith of Woodward Clyde were very helpful in creating spectra for inclusion in the database. Ron Tognazzini and Rulon Fronk of the Los Angeles Department of Water and Power (LADWP) provided valuable information on LADWP substations. Nitin Christopher, a graduate student at San Jose State University, performed some of the preliminary plots of fragility curves and damage data.

This work was supported in part by the Pacific Earthquake Engineering Research Center through the Earthquake Engineering Research Centers Program of the National Science Foundation under Award number EEC-9701568.

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(Note: All appendices and the database are available on the project website, http://www.engr.sjsu.edu/tanagnos/Substation/index.htm)

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(Note: All appendices and the database are available on the project website, which can be accessed from the project website http://www.engr.sjsu.edu/tanagnos/Substation/index.htm)

1 Introduction

The high voltage components of electrical power substations are critical elements in the reliable operation of the power grid. For the power grid to be capable of reliable delivery to a region immediately after an earthquake, these components must continue to function. The 1994 Northridge, California, earthquake demonstrated that damage to electrical substation components can have far reaching consequences. Communities in British Columbia, Montana, Wyoming, Idaho, Oregon, and Washington experienced outages as a result of damage to electrical substation components in the Los Angeles area (Schiff, 1995). Customers in the Los Angeles area experienced outages lasting anywhere from a few seconds to several days. Power was restored to all major substations and to about 95% of the customers within 24 hours (Schiff 1995). However, during the next few months extensive repair and replacement of equipment were required to restore the system to its pre-earthquake redundancy and capacity. As repaired, the systems are assumed to be more reliable than prior to the earthquake.

The power transmission and distribution systems in California have been built over many decades and utilize equipment that was designed and installed under varying seismic criteria. Substation equipment is very expensive and unfortunately many of the equipment components such as porcelain insulators and bushings are vulnerable to seismic damage. Some of the older equipment that was designed to much lower seismic standards is particularly vulnerable to seismic loading. The repair of substation damage caused by earthquakes can be a significant expenditure for utilities. Furthermore, loss of power immediately after an earthquake can disrupt emergency response and recovery operations for the affected region. Thus utilities are interested in ways to minimize or eliminate earthquake damage and disruption to their systems.

PG&E and other utilities have aggressive plans to replace vulnerable older equipment with more rugged components. Other mitigation strategies include retrofitting existing equipment, modifying design and installation practices, and developing improved standards for qualifying new equipment. A key element of the mitigation plans is the establishment of priorities based on, at minimum, equipment function, importance, and vulnerability. The analysis of substation equipment damage in past earthquakes is an important step in establishing levels of acceleration that cause failure in equipment, modes of failure and component weaknesses that lead to failure. The data can be used to develop or update fragility curves for use in system reliability models that can help in the establishment of mitigation priorities.

The substation network evaluation performed by PG&E (Matsuda et al., 1991) represents one type of study that has been used to establish priorities for mitigation. In that study, scenario earthquakes were developed and damage was estimated at key substations. Substations were ranked and then selected for analysis based on their exposure and on their importance to the continued operation of the system. The damage to key pieces of equipment was determined by considering damage to similar equipment in past earthquakes. The impact on customer service was assessed by considering the damage at each substation and the redundancy of transmission lines.

The purpose of this project was to compile equipment performance data from past earthquakes and organize the data into a database that would be useful in the analysis of equipment vulnerabilities. Anshel Schiff had collected extensive damage data for selected earthquakes and organized the information into a Filemaker Pro database. This database was used as the starting point for this study. Supplementary data relating to ground motions and undamaged equipment were collected for substations in the database. The database was then augmented with performance data that was developed from additional substations and earthquakes. Finally, for selected equipment classes the data were compared with existing fragility curves developed using expert opinion. Specific project tasks were to

- evaluate the existing database for content and quality;
- add ground motion data either from site recordings or from simulated ground motion based on earthquake-specific attenuation relations;

- add data from additional substations and earthquakes;
- review existing equipment classification system developed by the Utilities Working Group;
- document the database; and
- compare the data with existing fragility curves for selected classes of equipment.

2 Summary of Database and Contents

2.1 Format of Substation Equipment Database

The Substation Equipment Database described in this report is a modified and augmented version of the initial database developed by Anshel Schiff. The original database was in Filemaker Pro and–contained graphic representations of some pieces of equipment in addition to the written descriptions of equipment and damage. The database described here is maintained in an Excel 97 spreadsheet containing 68 columns of information. The content of each column is described in detail in Appendix A.

Early in the project, a decision was made to convert the substation equipment database from Filemaker Pro to Excel to better conform to software at PG&E. While converting the database made it more accessible to researchers at PEER and PG&E, it introduced several limitations. First, all of the graphical representations of equipment were lost in the conversion. Secondly, EXCEL limits on the number of characters that can be typed in a cell, and in a few cases, data were truncated during conversion. Every attempt has been made to retrieve and include the truncated data. Third, EXCEL is not a dedicated database manager, and thus is not designed for performing queries. However, with a little caution to prevent truncating data, the EXCEL file can be saved in a dBASE format and then the Microsoft Add-in Query or any other database manager can be used to perform queries.

2.2 Sources of Substation Equipment Damage Data

Data contained in the Substation Equipment Database were compiled from the following sources:

- original database developed by Anshel Schiff
- *Earthquake Spectra* articles
- Electric Power Research Institute (EPRI) reports

- American Society of Civil Engineers (ASCE) Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph No. 8
- internal PG&E reports
- internal Los Angeles Department of Water and Power (LADWP) report
- internal Southern California Edison reports
- PG&E RCMS database of transformers and circuit breakers
- single line drawings of specific substations; and
- discussions with individuals who performed post-earthquake reconnaissance at specific sites

The quality and completeness of the data vary considerably for different earthquakes and substations. The data collected for more recent California earthquakes, particularly Whittier Narrows, Loma Prieta, and Northridge, are much more detailed and complete than those for earlier events.

2.3 Summary of Data

The database contains information about damaged and undamaged substation equipment from 12 earthquakes as detailed in Table 2.1. Pacific Gas & Electric, Los Angeles Department of Water and Power, Southern California Edison, and the California Department of Water Resources own the equipment documented in the database. The majority of data relates to equipment operating at 220/230 kV and 500 kV. In a very small number of cases, the damage to 60 kV equipment is documented.

The quality of the data varies considerably. For substations in the Loma Prieta and Northridge earthquakes, detailed reports were available that identified the locations and types of damage for key types of equipment. These reports also provided good statistics on the undamaged equipment. For most other earthquakes, undamaged equipment statistics were developed through discussions with key personnel, examination of single line drawings, and review of the PG&E RCMS database. As a result, some types of equipment such as wave traps, potential transformers, coupling current voltage transformers, lightning arresters, and disconnect switches are not well represented at many sites.

For each earthquake and substation, ground motion data were added. The database contains actual values for instrumented substations with site recordings. At other sites, ground motions are based on event-specific attenuation relations modified with residuals from recordings at nearby sites (Somerville and Smith, 1999). The ground motion values listed in Table 2.2 vary depending on their source. For the ground motions generated from event-specific attenuation relations, two horizontal components, fault normal and fault parallel, were available and the largest value was chosen. Only one horizontal ground motion spectrum was available for ground motions generated from the attenuation relationship developed by Abrahamson and Silva (1997). In the case of site recordings, the two components are determined by the orientation of the instrument. The soil types listed in Table 2.2 are rough descriptions of the soil at the site and do not take into account local variations at the site. Since substations cover many acres, soil conditions can vary dramatically over the site.

As summarized in Table 2.2, the peak ground acceleration, 0.1-second spectral acceleration, 0.2-second spectral acceleration and 0.3 second acceleration ground motions are included in the database. These values were chosen because they are in the range of the fundamental period of most pieces of equipment. It should be noted that the response of equipment may be substantially altered by the support system. For example, a disconnect switch that is mounted on a very flexible frame will have a different response than a similar disconnect switch mounted on a frame. The support system may have periods much longer than 0.3 seconds. For information about longer periods, the complete 5% damped response spectra provided by Somerville and Smith (1999) are found in Appendix B.

Table 2.3 contains a summary of the equipment data contained in the database. The data is sorted by earthquake and substation. For each substation, the peak ground acceleration is listed along with the number of damaged and undamaged pieces of equipment contained in the database. In the table, each piece of equipment is listed according to the classification system discussed in Section 4; however, in the database more complete descriptions may be available. For example, information about the support frame or the anchorage may be included in a comment field.

In this study, if a phase has a separate piece of equipment associated with it, such as one phase of a circuit breaker, it is considered as a separate item of equipment. Thus, for earthquake damage purposes, a circuit breaker would consist of three equipment items rather than one. A transformer bank consisting of three single-phase transformers would be considered as three pieces of equipment while a three-phase transformer would be considered as a single piece of equipment.

It should be emphasized that this is not how the industry defines a piece of equipment. For the purposes of damage estimation this definition does have its advantages. For example, the number of phases damaged can impact the cost of repair and the time to restore equipment to service. Sometimes different phases are connected differently to other equipment. By representing damage by phase, failures due to interaction may be more readily identified. Using damage data for each phase of equipment allows for the development of fragilities for each phase. Simple models then can be developed to combine the probabilities of failure of each phase to estimate the probability that one, two or three phases will be out of service.

Table 2.1: Earthquakes and Substations Represented in Substation Equipment Database

Earthquake	Substations	
San Fernando (2/9/71, M_w = 6.6)	SS#1 SS#8 SS#18 SS#19	SS#23 SS#41 SS#45 SS#44
Point Mugu (2/21/73, M_w = 5.3)	SS#40	
Santa Barbara (8/13/78, M_w = 6.0)	SS#13	
Coalinga (5/2/83, M_w = 6.4)	SS#12	
Morgan Hill (4/24/84, M_w = 6.2)	SS#20 SS#21	SS#24
North Palm Springs (7/8/86, M_w = 6.0)	SS#7	
Whittier Narrows (10/1/87, M_w = 6.0)	SS#1 SS#4 SS#6 SS#8 SS#10 SS#15 SS#16 SS#17 SS#19	SS#22 SS#23 SS#27 SS#29 SS#30 SS#32 SS#42 SS#43 SS#46
Whittier Narrows Aftershock (10/4/87, M_w = 5.3)	SS#1 SS#2 SS#4 SS#6	SS#8 SS#11 SS#15 SS#33
Tejon Ranch (6/10/88, M_L = 5.2)	SS#9	
Sierra Madre (6/28/91, M_w = 5.8)	SS#14	
Loma Prieta (10/17/89, M_w = 7.0)	SS#24 SS#25 SS#26 SS#28 SS#39	
Landers (6/28/92, M_w = 7.3)	SS#5	
Northridge (1/17/94, M_w = 6.7)	SS#3 SS#31 SS#34 SS#35 SS#36 SS#37	SS#38 SS#41 SS#44 SS#45

Table 2.2: Summary of Substation Sites and Ground Motions

Substation	Owner	Soil Type	Peak Acc.	0.1 Second Spectral Acc.	0.2 Second Spectral Acc.	0.3 Second Spectral Acc.	Strong Motion Record at Site	Source of Spectrum
Coalinga								
SS#12	PG&E	(UBC S1), < 200 ft alluvium overlying sedimentary rock.	0.30g	0.57g	0.66g	0.53g	No	Abrahamson and Silva, 1997 attenuation
Landers								
SS#5	SCE	Quaternary formation — soil	0.35g	0.49g	0.81g	1.29g	Yes	recording
Loma Prieta								
SS#24	PG&E	(UBC S1), < 30 ft alluvium overlying sedimentary rock, (NEHRP D — stiff soil 180m/s<Vs<=360 m/s)	0.22g	0.33g	0.43g	0.54g	No	event-specific attenuation
SS#25	PG&E	(UBC S1), < 20 ft alluvium overlying sedimentary rock, (NEHRP C — very dense soil and soft rock 360 m/s<Vs<=760 m/s)	0.24g	0.35g	0.47g	0.58g	No	event-specific attenuation
SS#26	PG&E	(UBC S2), >2000 ft alluvium with some <20 ft soft clay layers overlying sedimentary rock, (NEHRP D — stiff soil 180m/s<Vs<=360 m/s)	0.22g	0.32g	0.43g	0.54g	No	event-specific attenuation
SS#28	PG&E	(UBC S3), >500 ft alluvium/estuarine with some >20 ft bay mud layers overlying metavolcanic rock, (NEHRP D — stiff soil 180m/s<Vs<=360 m/s)	0.13g	0.21g	0.29g	0.36g	No	event-specific attenuation
SS#39	PG&E	(UBC S2), <20 ft bay mud overlying >200 ft alluvium/estuarine overlying metavolcanic rock, (NEHRP E — soft clay Vs<=180 m/s)	0.10g	0.20g	0.30g	0.40g	No	event-specific attenuation

Table 2.2 (cont.): Summary of Substation Sites and Ground Motions

Substation	Owner	Soil Type	Peak Acc.	0.1 Second Spectral Acc.	0.2 Second Spectral Acc.	0.3 Second Spectral Acc.	Strong Motion Record at Site	Source of Spectrum
			Morgan Hill					
SS#20	PG&E							
SS#21	PG&E	less than 200 ft alluvium overlying metavolcanic rock: UBC S1 NEHRP D: stiff soil (180m/s<Vs<=360 m/s)	0.043g	0.081g	0.10g	0.10g	No	Abrahamson and Silva, 1997 attenuation
SS#24	PG&E	less than 30 ft alluvium overlying sedimentary rock: UBC S1 NEHRP D: stiff soil (180m/s<Vs<=360 m/s)	0.24g	0.42g	0.53g	0.51g	No	Abrahamson and Silva, 1997 attenuation
			North Palm Springs					
SS#7	SCE	Quaternary formation — alluvial fan deposits	1.14g	1.99g	1.71g	1.27g	Yes	recording
			Northridge					
SS#3	LADWP	Quaternary formation — soil	0.29g	0.46g	0.73g	0.66g	No	event-specific attenuation
SS#31	SCE	Quaternary formation — soil	0.54g	0.65g	0.68g	0.66g	Yes	recording
SS#34	LADWP	Tertiary formation — soft rock	0.90g	1.00g	1.45g	1.82g	Yes	recording
SS#35	LADWP	Quaternary formation — soil	0.45g	0.88g	0.86g	1.29g	Yes	recording
SS#36	LADWP	Tertiary formation — soft rock	0.45g	0.72g	1.04g	1.03g	No	event-specific attenuation
SS#37	LADWP		unknown				No	
SS#38	LADWP	Quaternary formation — soil	0.38g	0.64g	0.95g	0.90g	No	event-specific attenuation
SS#41	SCE	Quaternary formation — soil	0.56g	0.83g	1.12g	1.37g	No	event-specific attenuation
SS#44	LADWP	Quaternary formation — soil	0.80g	0.99g	1.18g	1.25g	Yes**	recording
SS#45	SCE	Mesozoic formation — hard rock	0.13g	0.23g	0.33g	0.32g	Yes	event-specific attenuation

** Recording was at nearby SS#47

Table 2.2 (cont.): Summary of Substation Sites and Ground Motions

Substation	Owner	Soil Type	Peak Acc.	0.1 Second Spectral Acc.	0.2 Second Spectral Acc.	0.3 Second Spectral Acc.	Strong Motion Record at Site	Source of Spectrum
Point Mugu								
SS#40	SCE	Quaternary formation — soil	0.12g	0.22g	0.25g	0.24g	Yes*	Abrahamson and Silva, 1997 attenuation
San Fernando								
SS#1	SCE	Quaternary formation — soil	0.07g	0.12g	0.20g	0.18g	No	event-specific attenuation
SS#8	SCE	Mesozoic formation — hard rock	0.23g	0.36g	0.59g	0.49g	No	event-specific attenuation
SS#18	SCE	Quaternary formation — soil	0.14g	0.24g	0.41g	0.36g	No	event-specific attenuation
SS#19	SCE	Quaternary formation — soil	0.10g	0.18g	0.31g	0.27g	No	event-specific attenuation
SS#23	SCE	Quaternary formation — soil	0.15g	0.25g	0.44g	0.39g	No	event-specific attenuation
SS#41	SCE	Quaternary formation — soil	0.56g	0.92g	1.65g	1.57g	No	event-specific attenuation
SS#45	SCE	Mesozoic formation — hard rock	0.19g	0.30g	0.52g	0.39g	No	event-specific attenuation
Santa Barbara								
SS#13	SCE	Tertiary formation — soft rock	0.25g	0.52g	0.86g	0.54g	Yes	recording
Sierra Madre								
SS#14	SCE	Quaternary formation — soil	0.21g	0.39g	0.45g	0.42g	No	Abrahamson and Silva, 1997 attenuation

* recording was not used due to high noise level

Table 2.2 (cont.): Summary of Substation Sites and Ground Motions

Substation	Owner	Soil Type	Peak Acc.	0.1 Second Spectral Acc.	0.2 Second Spectral Acc.	0.3 Second Spectral Acc.	Strong Motion Record at Site	Source of Spectrum
Tejon Ranch								
SS#9	CDWR	Firm	0.10g				Yes	recording
Whittier Narrows								
SS#1	SCE	Quaternary formation — soil	0.09g	0.18g	0.22g	0.18g	No	event-specific attenuation
SS#4	SCE	Quaternary formation — soft alluvium	0.22g	0.41g	0.51g	0.43g	No	event-specific attenuation
SS#6	SCE	Quaternary formation — soil	0.15g	0.28g	0.36g	0.30g	No	event-specific attenuation
SS#8	SCE	Mesozoic formation — hard rock	0.23g	0.41g	0.56g	0.41g	No	event-specific attenuation
SS#10	SCE	Quaternary formation — soil	0.12g	0.26g	0.31g	0.24g	No	event-specific attenuation
SS#15	SCE	Mesozoic formation — hard rock	0.19g	0.34g	0.45g	0.36g	No	event-specific attenuation
SS#16	SCE	Quaternary formation — soil	0.13g	0.24g	0.30g	0.26g	No	event-specific attenuation
SS#17	SCE	Quaternary formation — soil	0.11g	0.25g	0.30g	0.23g	No	event-specific attenuation
SS#19	SCE	Quaternary formation — soft alluvium	0.18g	0.33g	0.43g	0.38g	Yes	event-specific attenuation
SS#22	SCE	Quaternary formation — soil	0.12g	0.24g	0.29g	0.22g	No	event-specific attenuation
SS#23	SCE	Quaternary formation — firm soil	0.23g	0.53g	0.57g	0.44g	No	event-specific attenuation
SS#27	SCE	Quaternary formation — soil	0.25g	0.49g	0.57g	0.48g	No	event-specific attenuation
SS#29	SCE	Tertiary formation — soft rock	0.45g	0.67g	1.02g	0.99g	No	event-specific attenuation

Table 2.2 (cont.): Summary of Substation Sites and Ground Motions

Substation	Owner	Soil Type	Peak Acc.	0.1 Second Spectral Acc.	0.2 Second Spectral Acc.	0.3 Second Spectral Acc.	Strong Motion Record at Site	Source of Spectrum
Whittier Narrows (cont.)								
SS#30	SCE	Quaternary formation — soil	0.51g	0.82g	0.90g	0.62g	Yes	recording
SS#32	SCE	Quaternary formation — soil	0.24g	0.43g	0.51g	0.42g	No	event-specific attenuation
SS#42	SCE	Quaternary formation — soil	0.25g	0.53g	0.62g	0.49g	No	event-specific attenuation
SS#43	SCE	Quaternary formation — soil	0.24g	0.44g	0.56g	0.47g	No	event-specific attenuation
SS#46	SCE	Quaternary formation — soil	0.24g	0.50g	0.59g	0.50g	No	event-specific attenuation
Whittier Narrows — Aftershock								
SS#1	SCE	Quaternary formation — soil	0.06g	0.11g	0.13g	0.12g	No	event-specific attenuation
SS#2	SCE	Quaternary formation — soil	0.20g	0.33g	0.40g	0.41g	No	event-specific attenuation
SS#4	SCE	Quaternary formation — soil	0.11g	0.22g	0.23g	0.21g	No	event-specific attenuation
SS#6	SCE	Quaternary formation — soil	0.08g	0.16g	0.17g	0.15g	No	event-specific attenuation
SS#8	SCE	Mesozoic formation — hard rock	0.11g	0.23g	0.31g	0.15g	No	event-specific attenuation
SS#11	SCE	Quaternary formation — soil	0.11g	0.17g	0.19g	0.21g	No	event-specific attenuation
SS#15	SCE	Mesozoic formation — hard rock	0.08g	0.16g	0.22g	0.10g	No	event-specific attenuation
SS#23	SCE	Quaternary formation — firm soil	0.22g	0.38g	0.43g	0.38g	No	event-specific attenuation
SS#33	SCE	Tertiary formation — soft rock	0.18g	0.33g	0.42g	0.32g	No	event-specific attenuation

Table 2.3: Summary of 230 kV and 500 kV Substation Equipment in Database

Earthquake	Substation	PGA	Utilities Working Group Class▲	Damaged (# items)	Undamaged (# items)
Coalinga	SS#12	0.30g	CB15A	1	8
			CB20A	0	33
			CB74	0	6
			LA5	1	3
			TR1	0	3
			TR3	4	0
Landers	SS#5	0.35g	CB20A	0	24
			DS3	6	48
			LA1	0	15
			TR2	0	5
Loma Prieta	SS#24	0.22g	CB9	0	6
			CB20	0	18
			CB20A	0	24
			CB72s	7	2
			CB77	0	3
			CC1	0	25
			CC5	0	6
			CT5	6	3
			DS1	1**	23
			DS2	0	35
			DS3	0	20
			LA1*	1	12
			LA5*	0	4
			TR1	0	9
			TR3	4	3
			WT1	0	5
			WT2	0	6
	SS#25	0.24g	CB20	0	3
			CB20A	0	21
			CB78	0	3
			CC1	1	2
			DS3	6	117
			LA1	6	4
			TR1	3	7
			WT1*	0	3
			Bus Support	3	0*

* High likelihood of more items at the site
** Interaction failure likely
▲ Descriptions of Utilities Working Group Classes are found in Table 4.1

Table 2.3 (cont.): Summary of 230 kV and 500 kV Substation Equipment in Database

Earthquake	Substation	PGA	Utilities Working Group Class	Damaged (# items)	Undamaged (# items)
Loma Prieta	SS#26	0.22g	CB20A	2**	34
			CB72s	12	0
			CB77	0	3
			CC1	0	4
			CC5	6	3
			CT5	10	2
			DS1	25	17
			DS2	12**	0
			DS2*	1	2
			DS3*	1	115
			LA1*	0	8
			LA5*	0	4
			TR1	0†	16
			TR3	0†	4
			TR4	0†	1
			WT1	0	4
			WT2	2	4
			500kV Rigid Bus*	2	4
	SS#28	0.13g	CB9	2	7
			CB20A	0	32
			TR1	0	9
	SS#39	0.10g	CB9	3	0
			CB14	7	2
			CB20A	0	24
			CC1	2	1
			DS3	7	2*
			LA1	0	10
			TR1	4	6
			Bus Support	6	0*
Morgan Hill	SS#20		CS (115 kV)	1	0
	SS#21	0.043g	CB15	0	6
			CB15A	1	2
			CB20	0	6
			CB20A	0	3
			CB72	7	11
			CB74	0	18
			TR1	0	3
			TR3	0	3

* High likelihood of more items at the site
** Interaction failure likely
† Minor oil leaks with no impact on service

Table 2.3 (cont.): Summary of 230 kV and 500 kV Substation Equipment in Database

Earthquake	Substation	PGA	Utilities Working Group Class	Damaged (# items)	Undamaged (# items)
Morgan Hill	SS#24	0.24g	CB9	0	6
			CB20	0	15
			CB20A	0	12
			CB72s	1	11
			CB74	0	15
			CC1*	0	1
			CC5	0	5
			CT5	0	12
			DS1	0	24
			DS2*	0	6
			LA1*	1	13
			LA5	0	7
			TR1	0	9
			TR3	0	7
			WT2	0	4
North Palm Springs	SS#7	1.14g	CB5	6	0
			CB9	6	0
			CB20	0	9
			CB20A	0	24
			CB73	0	3
			CC5	4	2
			CT5	8	1
			DS1	9	18
			DS3	6	84
			LA1	7	2
			LA5	9	1
			PT1	6	0
			PT5	10	0
			TR2	0	4
			TR3	4	0
			WT2	2	2
			MODS	6	3
			Post Insulator*	70	8
			Shunt Reactor	4	2
Northridge	SS#3	0.29g	LA1	1	20
			TR2	3	4
	SS#31	0.54g	CB9	7	2
			CB14	15	0
			CB20	0	45
			CC1	19	26
			DS3	138††	0
			PT1	0	6
			WT1	0	13

* High likelihood of more items at the site

†† 75 phases only required readjustment

Table 2.3 (cont.): Summary of 230 kV and 500 kV Substation Equipment in Database

Earthquake	Substation	PGA	Utilities Working Group Class	Damaged (# items)	Undamaged (# items)
Northridge	SS#34	0.90g	CB20	0	87
			CC1	14	40
			CC5	3	3
			DS1	6	0
			DS3	18	156
			LA5	2	6
			PT1	0	6
			TR1	12	0
			TR3	9	0
			WT1	11	4
			WT2	3	3
	SS#35	0.45g	CB20A	0	114
			CC1	0	27
			CS2	3	3
			DS2	1	119
			DS1	2	4
			LA1	3	18
			LA5	3	0
			PT1	1	1
			PT5	0	3
			TR2	2	5
			TR3	0	6
			WT1	1	4
			WT2	0	3
			Pothead	0	9
	SS#36	0.45g	CB20A	0	72
			CC1	0	24
			PT1	0	6
			DS2	18	54
			LA1	9	3
			TR2	3	1
			WT1	1	7
	SS#37	unknown	CB	no CBs at site	
			LA1	6	3
			TR2	2	1
	SS#38	0.38g	CB20A	0	54
			CC1	0	18
			DS3	90	27
			LA1	11	10
			PT1	2	0*
			TR1	2	2
			WT1	3	1
			Pothead	0	9

Table 2.3 (cont.): Summary of 230 kV and 500 kV Substation Equipment in Database

Earthquake	Substation	PGA	Utilities Working Group Class	Damaged (# items)	Undamaged (# items)
Northridge	SS#41	0.56g	CB	No CBs at site	
			DS3	0	6
			LA1	0	6
			TR2	1	1
	SS#44	0.80g	CB20	0	12
			CB20A	0	45
			CC1	3	33
			CS1	17	0
			DS3‡	25	101
			LA1	0	12
			PT1	4	8
			TR2	1	1
			WT1	2	5
	SS#45	0.13g	CB15	1	8
			CB20	0	33
			CB57	0	21
			CB72s	2	4
			CB73	0	9
			CB77	0	6
			CT1	0	24
			CT5	2	13
			DS1	21	45
			DS3	0	108
			LA1	0	10
			LA5	7	21
			TR3	3	7
			WT2	0	10
			Post Insulator*	4	60
Pt. Mugu	SS#40	0.12g	CB20A	0	54
			DS3	0	108
			LA1	0	6
			TR2	0	2
San Fernando	SS#1	0.07g	CB20	0	75
			DS3	0	150
			LA1	0	24
			TR1	0	13
			TR2	0	6
	SS#8	0.23g	CB20	0	6
			CB20A	0	12
			DS3	0	42
			LA1	0	7
			TR1	0	7

* High likelihood of more items at the site

‡ 24 phases mounted on heavily braced support structures

Table 2.3 (cont.): Summary of 230 kV and 500 kV Substation Equipment in Database

Earthquake	Substation	PGA	Utilities Working Group Class	Damaged (# items)	Undamaged (# items)
San Fernando	SS#18	0.14g	CB20	0	54
			DS3	0	108
			LA1	0	15
			TR2	0	5
	SS#19	0.10g	CB9	1	5
			CB20	0	39
			CB20A	0	3
			DS3	0	102
			LA1	0	6
			TR1	0	6
	SS#41	0.56g	DS3	4	2*
			LA1	1	6
			TR1	1	6
	SS#44		CB9	33	0
			PT1	10	2
	SS#45	0.19g	CB15	0	12
			CB20	0	48
			CB72	9	9
			DS1*	1	17
			DS3	0	96
			LA1	0	10
			LA5	1	24
			TR3	2	8
			Post Insulator	2	106
Santa Barbara	SS#13	0.25g	CB20A	0	12
			DS3	0	36
			LA1	0	12
			PT1	0	6
			TR1	7	5
Sierra Madre	SS#14	0.21g	CB14	5	7
			DS3	0	30
			TR2	0	2
Tejon Ranch	SS#9	0.10g	CB14	10†	8
			DS2	1	77
			LA1	0	24
			TR2	1	7
Whittier Narrows	SS#1	0.09g	CB9	2	10
			CB20	0	63
			DS3	0	150
			LA1	0	24
			TR1	1	12
			TR2	0	6

* High likelihood of more items at the site
† Includes one phase on base isolators

Table 2.3 (cont.): Summary of 230 kV and 500 kV Substation Equipment in Database

Earthquake	Substation	PGA	Utilities Working Group Class	Damaged (# items)	Undamaged (# items)
Whittier Narrows	SS#4	0.22g	CB9	6	0
			CB20	1	17
			CB20A	0	18
			DS3	0	84
			LA1	0	12
			TR1	0	6
			TR2	1	2
	SS#6	0.15g	CB9	9	21
			DS3	0	66
			LA1	0	9
			TR2	0	3
	SS#8	0.23g	CB20	0	6
			CB20A	0	12
			DS3	0	42
			LA1	0	7
			TR1	0	7
	SS#10	0.12g	CB9	0	6
			CB14	0	6
			CB20	0	12
			CB20A	0	6
			DS3	0	66
			LA1	0	6
			TR2	0	2
	SS#15	0.19g	CB20	0	12
			DS3	0	30
			LA1	0	6
			TR1	0	6
	SS#16	0.13g	CB14	5	10
			CB20	0	12
			CB20A	0	12
			DS3	0	78
			LA1	0	6
			TR2	0	2
	SS#17	0.11g	CB9	1	23
			CB20	0	36
			DS3	0	120
			LA1	0	9
			TR2	0	3
	SS#19	0.18g	CB9	3	3
			CB20	0	39
			CB20A	0	3
			DS3	0	102
			LA1	0	6
			TR1	0	6
			TR2	0	1

Table 2.3 (cont.): Summary of 230 kV and 500 kV Substation Equipment in Database

Earthquake	Substation	PGA	Utilities Working Group Class	Damaged (# items)	Undamaged (# items)
Whittier Narrows	SS#23	0.23g	CB9	24‡	0
			CB20	0	36
			DS3	0	120
			LA1	1	5
			TR2	0	2
	SS#30	0.51g	CB20A	0	21
			DS3	0	48
			LA1	0	10
			TR1	5	5
	SS#46	0.24g	CB20A	1	23
			DS3	0	57
			LA1	0	9
			TR2	1	2
Whittier Narrows Aftershock	SS#4	0.11g	CB9	1	2*
			TR2	2	1
	SS#6	0.08g	CB9	3	27

* High likelihood of more items at the site
‡ 17 CB9 functional immediately after earthquake, but eventually developed leaks

2.4 Limitations of Damage Data

While the data summarized in Section 2.3 can be used to perform statistical analyses on substation equipment, the data should be used with caution. There are a number of limitations that may make it difficult to draw specific conclusions or to make comparisons with fragility curves. Some of these limitations are detailed below.

Undamaged equipment may be missing from database — Particularly for older earthquakes, reconnaissance teams only documented damaged equipment. Estimates of undamaged equipment were developed from looking at single line drawings of substations or the PG&E RCMS database. In some cases, available single lines indicate the current situation, which may differ from the configuration at the time of the earthquake. Similarly, the RCMS database includes transformers and circuit breakers that are currently at the substation. Individuals familiar with the substation helped to identify when and what types of changes in equipment may have occurred.

Damaged equipment is not always visibly damaged — It is not always clear from walking through a site if equipment has been damaged. Slightly damaged equipment may not malfunction until later. For example, due to a gasket leak, a circuit breaker may experience a slow loss of sulfur-hexafluoride (SF-6) gas and only start to malfunction after most of the gas has been released. Someone visiting the site immediately after an earthquake may not identify this as a piece of damaged equipment. Similarly, a disconnect switch may be out of alignment, but because it is open or overhead and may be difficult to see, the problem may be overlooked. A complete reconnaissance report requires several visits to a substation after an earthquake to talk with operators for the purpose of validating damage data. For more recent earthquakes this has been done, but with older earthquakes, some damaged equipment may have been overlooked.

Equipment may be damaged but functional — For the purposes of evaluating the performance of the power grid immediately after an earthquake, the analyst is most interested in equipment that will not be functional. A transformer with sheared anchorage bolts that has slid several inches is technically damaged but may still function properly and will be taken off-line later to repair the anchorage details. Another example of a difficulty in analyzing damage data is disconnect switches that are out of alignment. These switches may sometimes be manually closed or tied shut to maintain the integrity of the network, but can be realigned or replaced later. The database does not always indicate whether damaged equipment was functional or not.

The type of damage may be unclear — Depending on the quality of the reconnaissance report, the type and severity of equipment damage may not be specified. For example, one or all of the support columns on a disconnect switch may be damaged. If only one column is damaged, it is possible that the switch can be repaired rapidly by replacing it with spares on the site. If all of the columns are damaged and the switch is lying on the ground, the switch may have to be replaced and the repair time will be longer. Since failure modes are not always included in the database, it may be difficult to compare damage data with specific fragility curves.

Damage due to interaction may not be identified — Damage to equipment may be caused by one piece of equipment pulling or pushing on another piece. It is possible that the same piece of equipment would not have been damaged if it had not been attached to anything else or if the conductor had more slack. Unfortunately, damage due to interaction is not always easy to identify after an earthquake. Except in a few cases, damage caused by interaction is not identified in the database.

The period of equipment motion may be altered by the support system — Similar types of equipment may be mounted on very different types of support systems. Support frames can be very stiff or very flexible. Some of the 230 kV equipment is mounted on tall bus structures, 60 feet above the ground. Using peak ground acceleration for developing fragility data does not account for the filtering of ground motion by the support structure. Similarly, the use of response spectra developed from ground motion records does not account for filtering of motion by the support structure.

Synthetic ground motions may not account for site specific ground conditions — Substation ground motions and spectra developed from event-specific attenuation relations are based on geologic conditions at the site. They do not take into account surface soils conditions, or variations in soil types and depths at the site. Thus, at best, they are only an approximation of the ground motion that may have actually occurred at the site.

Seismic design of equipment may not be identified — Greatly varying seismic requirements are used for some types of equipment. The database may lump all equipment into a single category , although some of the equipment may be seismically qualified. For example, older disconnect switches had no seismic design requirements or were designed for a low static coefficient, whereas new disconnect switches are shake table tested. Therefore the expected performance of newer switches can be greatly different than that of older switches.

3 Essential Parameters for Defining Equipment Fragilities

Figures 3.1 through 3.8 summarize the key parameters needed to define equipment fragilities from earthquake damage data. It is recommended that these data be collected for all equipment on future earthquake reconnaissance visits. The items in solid boxes are essential for a complete definition of the fragilities. The items in dashed boxes are less critical.

Each figure has two branches. The left branch describes attributes, specific to a particular type of equipment, which can be collected and cataloged before an earthquake. These attributes affect how the equipment will respond to a certain level of ground motion. For example, a composite insulator will be more rugged than a porcelain insulator; a well-braced radiator will perform better than one with no bracing. To some extent these parameters were used to develop the equipment classification system described in Section 4. The right branch describes the seismic input and the type of damage. These data can only be collected after the earthquake has occurred.

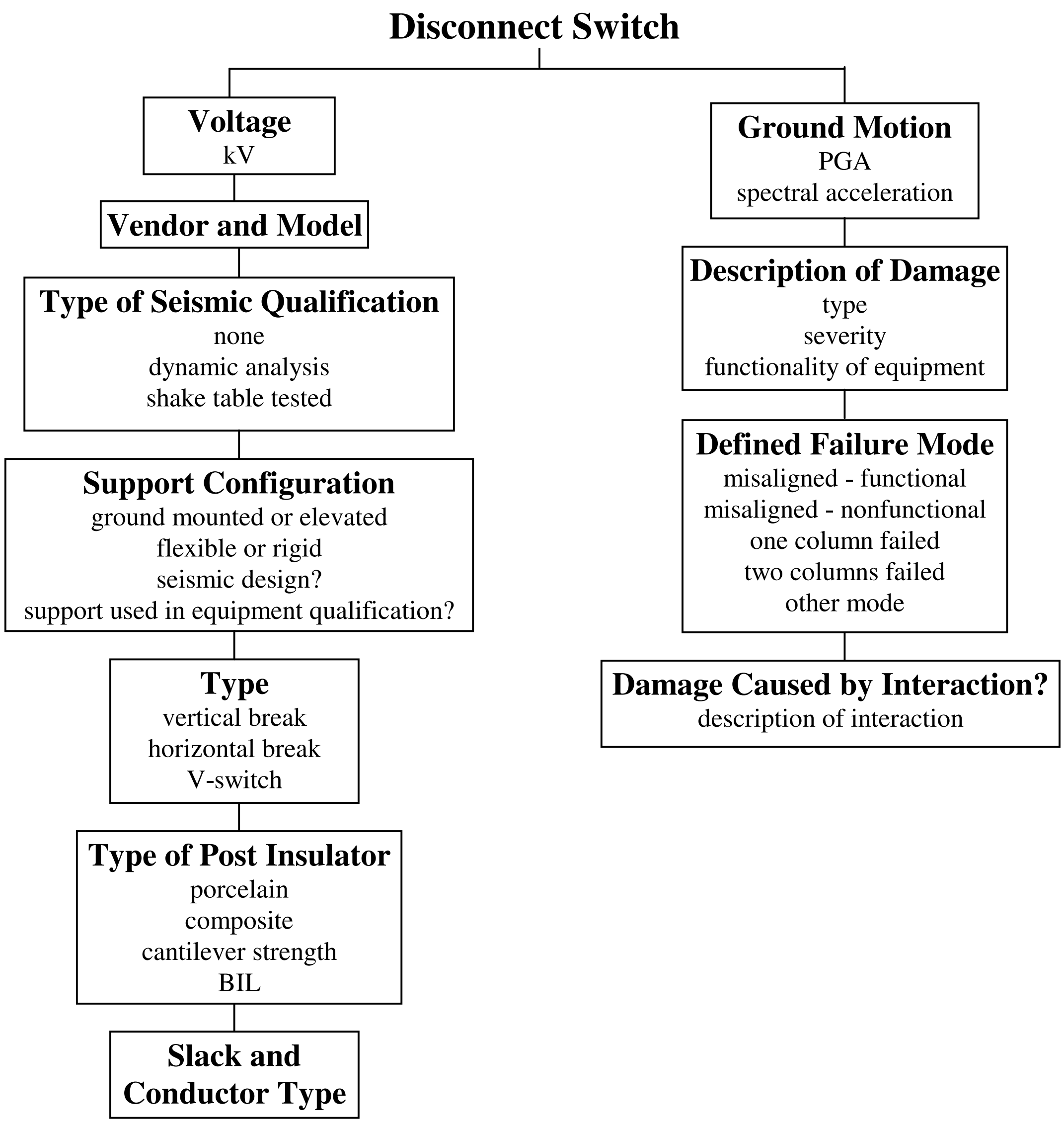

Figure 3.1 Key parameters for defining seismic damage to a disconnect switch

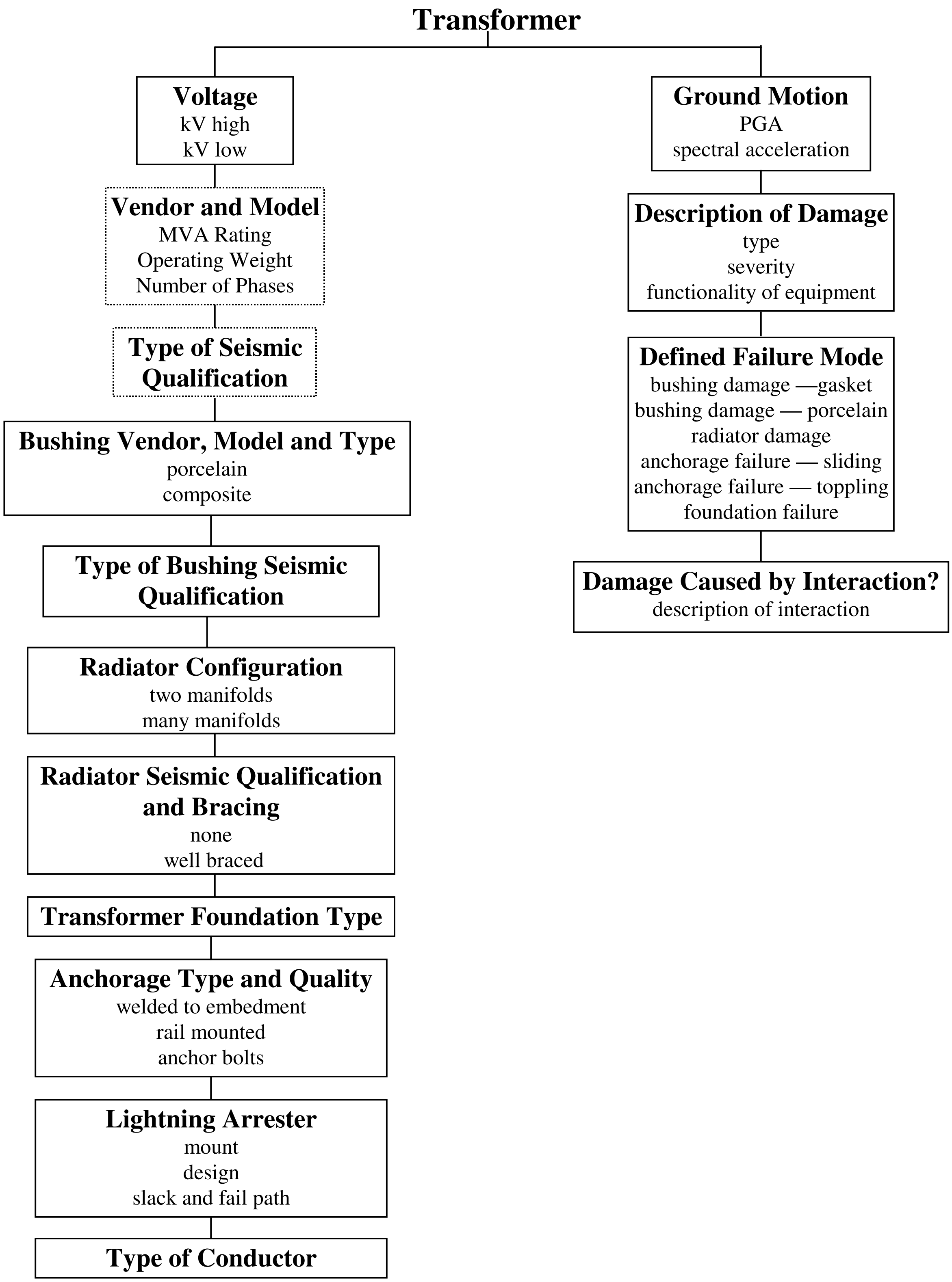

Figure 3.2 Key parameters for defining seismic damage to a transformer

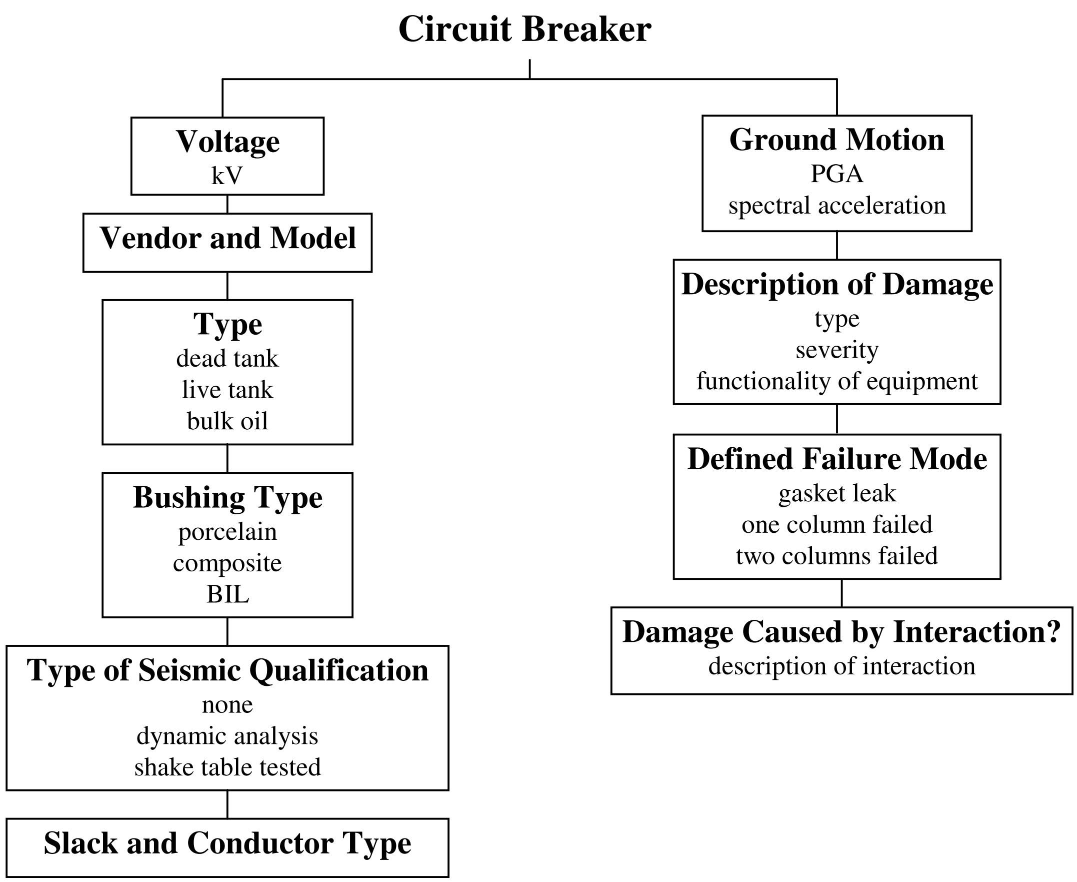

Figure 3.3 Key parameters for defining seismic damage to a circuit breaker

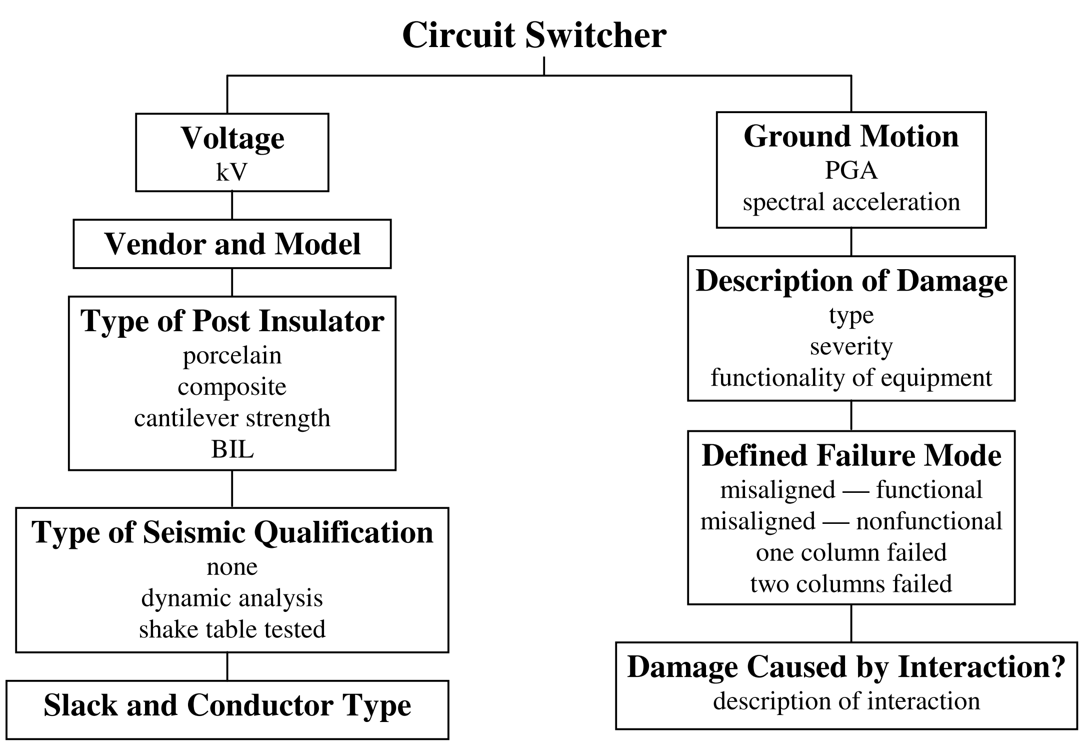

Figure 3.4 Key parameters for defining seismic damage to a circuit switcher

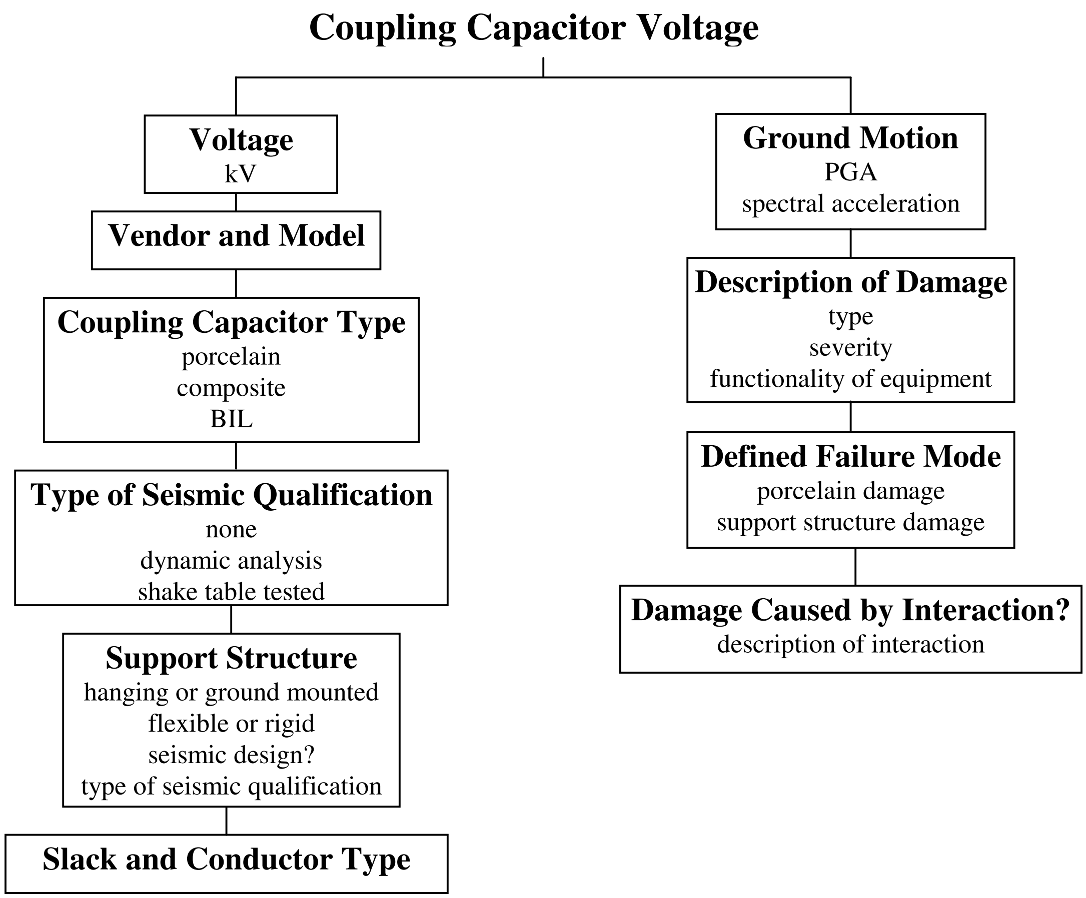

Figure 3.5 Key parameters for defining seismic damage to a coupling capacitor voltage transformer

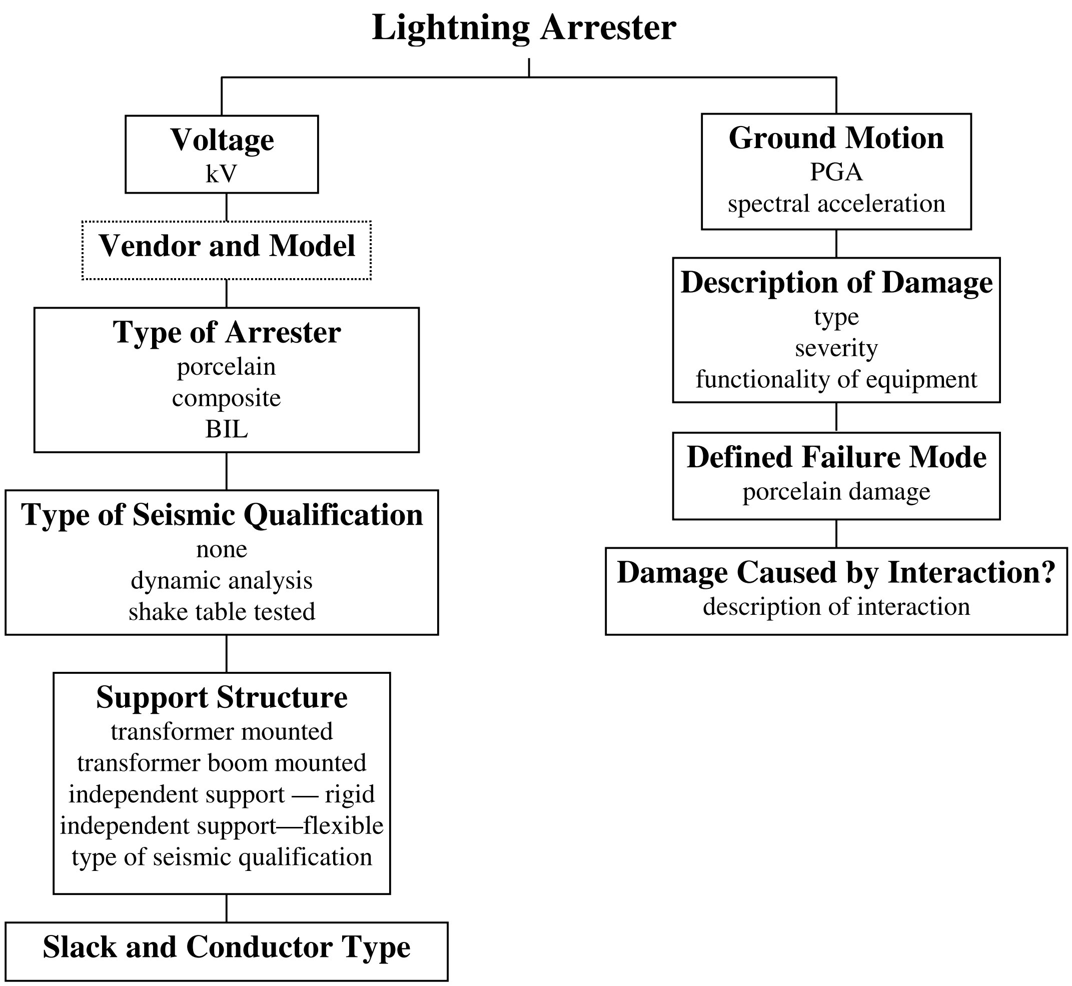

Figure 3.6 Key parameters for defining seismic damage to a lightning arrester

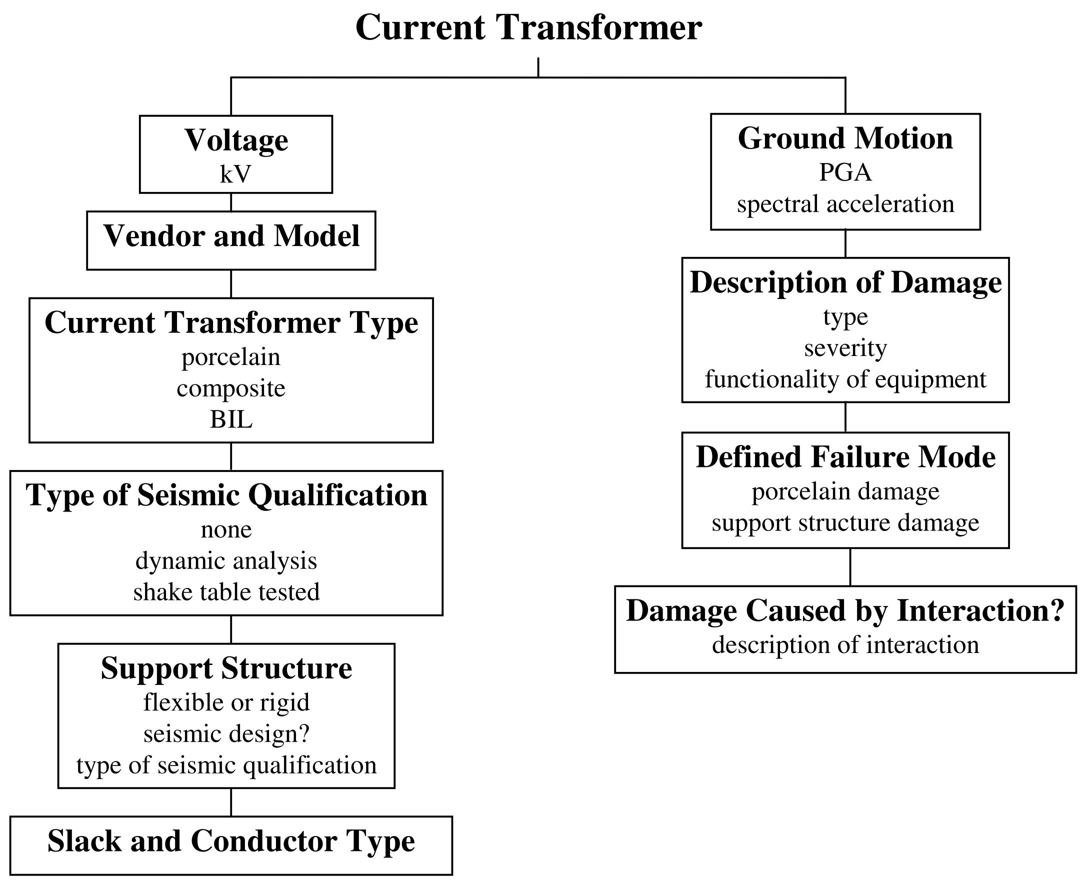

Figure 3.7 Key parameters for defining seismic damage to a current transformer

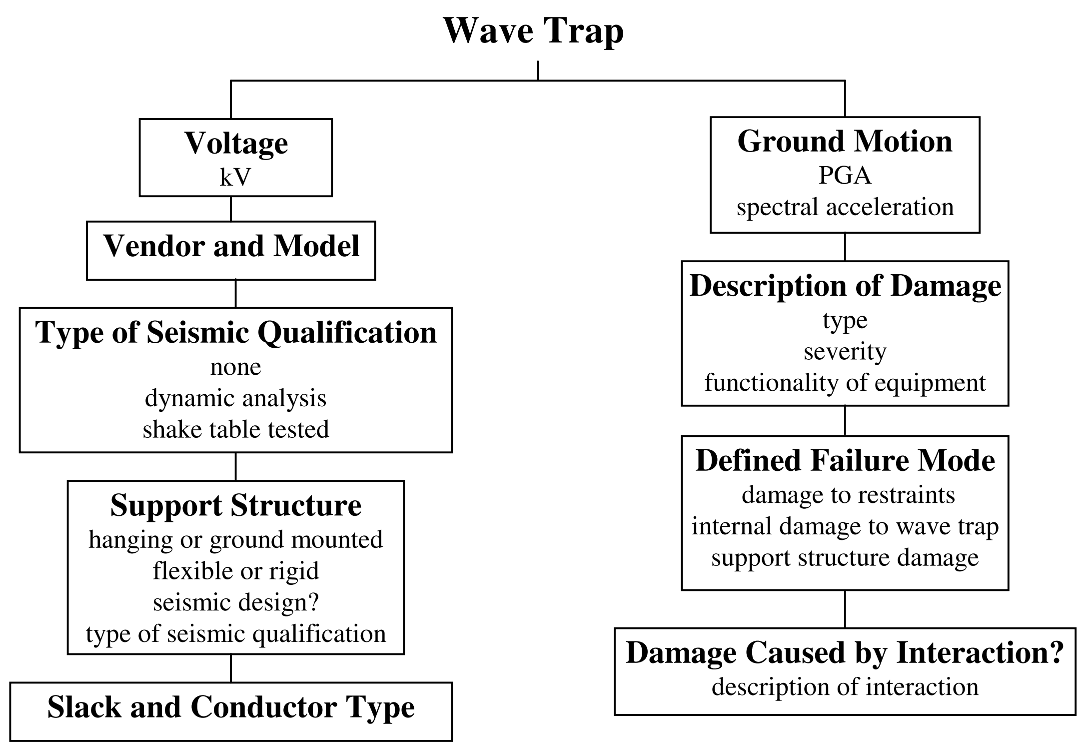

Figure 3.8 Key parameters for defining seismic damage to a wave trap

4 Utilities Working Group Equipment Classes

In September 1993, a group of experts from several California utilities convened to evaluate the quality of earthquake damage data available for developing equipment damage relationships. This Utilities Working Group (UWG) developed a standardized classification system for referring to substation equipment. The classification system referred only to equipment with voltage of 220 kV and higher, and was organized so that equipment with similar performance characteristics would be grouped together. For example, live tank circuit breakers have large tanks mounted on top of porcelain insulators, whereas dead tank breakers have the tank at the base. As a result, live tank circuit breakers tend to be more vulnerable to seismic motion than dead tank circuit breakers. The classification system has been modified somewhat in this report to simplify some categories. The classification system used in this study is summarized in Table 4.1.

For each of the UWG classes, the experts defined failure modes and developed opinion-based fragility curves. The fragility curves are described in more detail in Section 5 and Appendix C.

Table 4.1: Utilities Working Group Substation Equipment Classes

Transformer	
TR1	1-phase 230 kV transformer
TR2	3-phase 230 kV transformer
TR3	1-phase 500 kV transformer
TR4	3-phase 500 kV transformer
Circuit Breaker	
CB5	500 kV Cogenel old
CB9	230 kV live tank GE ATB4-6
CB14	230 kV live tank GE ATB7
CB15	500 kV live tank GE ATB
CB15a	500 kV live tank other
CB20	230 kV dead tank SF6
CB20a	230 kV dead tank oil
CB57	230 kV live tank modern
CB72	500 kV live tank WES-SF6
CB72s	500 kV live tank WES-SF6, seismically modified
CB73	500 kV live tank puffer
CB74	220 kV or 500 kV CB unknown
CB77	500 kV dead tank SF6
CB78	230 kV modern Brown Boveri dead tank SF6 (3 phase)
Disconnect Switch	
DS1	500 kV vertical switch
DS2	230 kV vertical switch
DS3	230 kV horizontal switch
MODS	230 kV Motorized Disconnect Switch

(continued)

Table 4.1 (cont.): Utilities Working Group Substation Equipment Classes

Lightning Arrester	
LA1	230 kV low seismic design
LA2	230 kV medium seismic design
LA3	230 kV high seismic design
LA4	230 kV composite column
LA5	500 kV low seismic design
LA6	500 kV medium seismic design
LA7	500 kV high seismic design
LA8	500 kV composite column
Current Transformer	
CT1	230 kV low seismic design
CT2	230 kV medium seismic design
CT3	230 kV high seismic design
CT4	230 kV composite
CT5	500 kV low seismic design
CT6	500 kV medium seismic design
CT7	500 kV high seismic design
CT8	500 kV composite
Coupling Capacitor Voltage Transformer	
CC1	230 kV low seismic design
CC2	230 kV medium seismic design
CC3	230 kV high seismic design
CC4	230 kV composite
CC5	500 kV low seismic design
CC6	500 kV medium seismic design
CC7	500 kV high seismic design
CC8	500 kV composite
Potential Transformer	
PT1	230 kV low seismic design
PT2	230 kV medium seismic design
PT3	230 kV high seismic design
PT4	230 kV composite
PT5	500 kV low seismic design
PT6	500 kV medium seismic design
PT7	500 kV high seismic design
PT8	500 kV composite
Wave Trap	
WT1	230 kV wave trap
WT2	500 kV wave trap
Circuit Switcher	
CS1	230 kV circuit switcher

5 Comparison of Database Statistics with Utilities Working Group Fragilities

Developing new fragility curves based solely on the available equipment damage data was beyond the scope of this project. In many cases, the damage data are insufficient to adequately define a fragility curve. Two key reasons for this are lack of data (too few points) or incomplete data (missing failure modes). To overcome these difficulties, Der Kiureghian is developing a methodology that uses Bayesian techniques to update the existing opinion-based fragility curves with the damage data.

For selected equipment, damage data is compared with opinion-based curves to provide a rough determination of whether the opinion-based curves are reasonable. Note that peak ground acceleration is used for the comparison, not because it is the best indicator of potential damage, but because the opinion-based fragility curves are defined using PGA. Parameters and plots of UWG fragilities for all equipment types are found in Appendix C.

5.1 Failure Modes

Comparison of equipment damage data with fragilities requires a standardized approach for reporting damage. As indicated in Figures 3.1 through 3.8, well-defined standardized failure modes are an essential element of the fragility curve definition. Failure modes that have been defined by the UWG are summarized in Table 5.1. In all cases where a number is used it should be read “at least.” For example, for TR2 or TR4, the third failure mode should read “At least 3 Main Porcelain Gasket Leaks.” These failure modes could be further refined by indicating whether the damaged equipment is functional or nonfunctional immediately after the earthquake.

For each type of equipment in the table, as one moves down the list, the failure modes are progressively more disruptive and expensive to repair. Some of the failure modes in Table 5.1 are mutually exclusive. In this case the relationship between the fragility curves is relatively simple and the probability of a failure mode can be determined by addition or subtraction. For example, for a three-phase transformer, at least one main bushing leak (L_1) is an exclusive event from at least two (L_2) or at least three main bushings leaking (L_3). Then the probability of exactly one column leaking is $P(L_2)$ - $P(L_1)$ and the probability of exactly two columns leaking is $P(L_3)$ - $P(L_2)$. In other cases the failure modes may occur simultaneously and may or may not be independent of one another. For example, it is possible to have anchorage failure (FM_1) with or without a major break (FM_2) in the radiator. In cases like this, the probability of damage defined as the occurrence of FM_1 or FM_2 or both may be determined using a fault tree. An example of such an approach is found in NIBS (1997).

Table 5.1: Failure Modes for Substation Equipment Classes

Equipment	Failure Modes
Single-Phase Transformers (TR1, TR3)	1 Main Porcelain Gasket Leak 1 Main Porcelain Break Major Break in Radiator Anchorage Failure Transformer Overturn
Three-Phase Transformers (TR2, TR4)	1 Main Porcelain Gasket Leak 2 Main Porcelain Gasket Leaks 3 Main Porcelain Gasket Leaks 1 Main Porcelain Break 2 Main Porcelain Breaks 3 Main Porcelain Breaks Major Break in Radiator Anchorage Failure Transformer Overturn
Live Tank Circuit Breakers (CB9, CB15, CB15A)	Column Base Gasket Leak 1 Porcelain Column Fails 2 Porcelain Columns Fail
Live Tank Circuit Breakers (CB72)	Head Porcelain Damage 1 Porcelain Column Fails 2 Porcelain Columns Fail 3 Porcelain Columns Fail
Live Tank Circuit Breakers (CB14, CB57, CB73)	1 Porcelain Column Fails 2 Porcelain Columns Fail
Dead Tank Circuit Breakers (CB20, CB77)	1 Porcelain Column Fails 2 Porcelain Columns Fail
Dead Tank Circuit Breakers (CB20A)	Anchorage Fails 1 Porcelain Column Fails 2 Porcelain Columns Fail
500 kV Cogenel Circuit Breaker (old)	Collapse of All Columns
500 kV Vertical Disconnect Switch	Misaligned Contacts Porcelain Column Fails
230 kV Disconnect Switch	Misaligned Contacts Broken Porcelain
Lightning Arrester	Failure of Porcelain Column
Current Transformer	Failure of Porcelain Column
Coupling Capacitor Voltage Transformer	Failure of Porcelain Column
Potential Transformer	Failure of Porcelain Column

5.2 Data Comparisons

Figure 5.1 shows the damage data for General Electric 230 kV live tank ATB4, ATB5, and ATB6 (CB9) plotted for each site along with the UWG fragility curves. The damage probabilities, plotted as solid triangles and an open square, are determined by dividing the number of damaged items by total number of items at a site. The plotted data do not include information about failure modes. In this figure, data from each site was plotted separately even though in some cases different sites experienced nearly identical peak ground accelerations. Data for sites with similar ground motion are combined in Figure 5.2.

Plotting data for each site is useful for identifying data that deviate significantly from the trend. These deviations may be due to site-specific factors such as soil conditions, ground motion duration, or installation procedures that can affect the amount of damage at a particular site. For example, it is possible that the soft soil at the SS#39 substation may account for the longer duration of shaking, or there may have been some other effect such as equipment interaction that caused the circuit breakers to fail at a lower PGA than would be expected. Another factor that may result in the high failure probability for SS#39 is that there was only one CB9 circuit breaker (Three Phases) at the site. A larger sample may have yielded a failure probability that was in better agreement with the data trend. In another case, the circuit breakers at SS#24 in both the Loma Prieta and Morgan Hill earthquakes seemed to have performed better than would be expected at that level of ground motion. It would be worth investigating why these circuit breakers performed so well. Also, it should be noted that ground motion is only reported for one location at a substation. Often this is at the control house. The site conditions at the control house may not be representative of the entire site. In particular, it is possible that the equipment under investigation is founded on a particularly good or bad soil.

Two different points represent the damage data for the SS#23 substation during the Whittier Narrows earthquake. This is because the performance of the circuit breakers immediately after the earthquake differs dramatically from the longer-term performance. The square shows that about 30% of the CB9's were functional immediately after the earthquake. Ultimately all the CB9's failed due to leaking gas (shown by the triangle).

Figures 5.1 and 5.2 suggest that the UWG fragility curves underestimate damage probabilities for ATB4, ATB5, and ATB6 circuit breakers. Among the limitations to this analysis is that a large number of the peak ground accelerations used to plot the data are based on attenuation relationships rather than on actual recordings. In addition, PGA is most likely not the best indicator of equipment performance. The fundamental period of this type of circuit breaker is about 0.2 seconds and spectral acceleration may be a better predictor of performance. As stated earlier, spectral acceleration also has limitations in predicting performance in that the support structure may significantly alter the period of the circuit breaker assembly. For comparison, the same damage data for ATB breakers are plotted versus 0.2-second spectral acceleration in Figure 5.3.

Clearly, in Figures 5.1 through 5.3, there are data that deviate significantly from the trend and from the expert-based curves. However additional data would be needed to provide recommendations about how the curves should be altered.

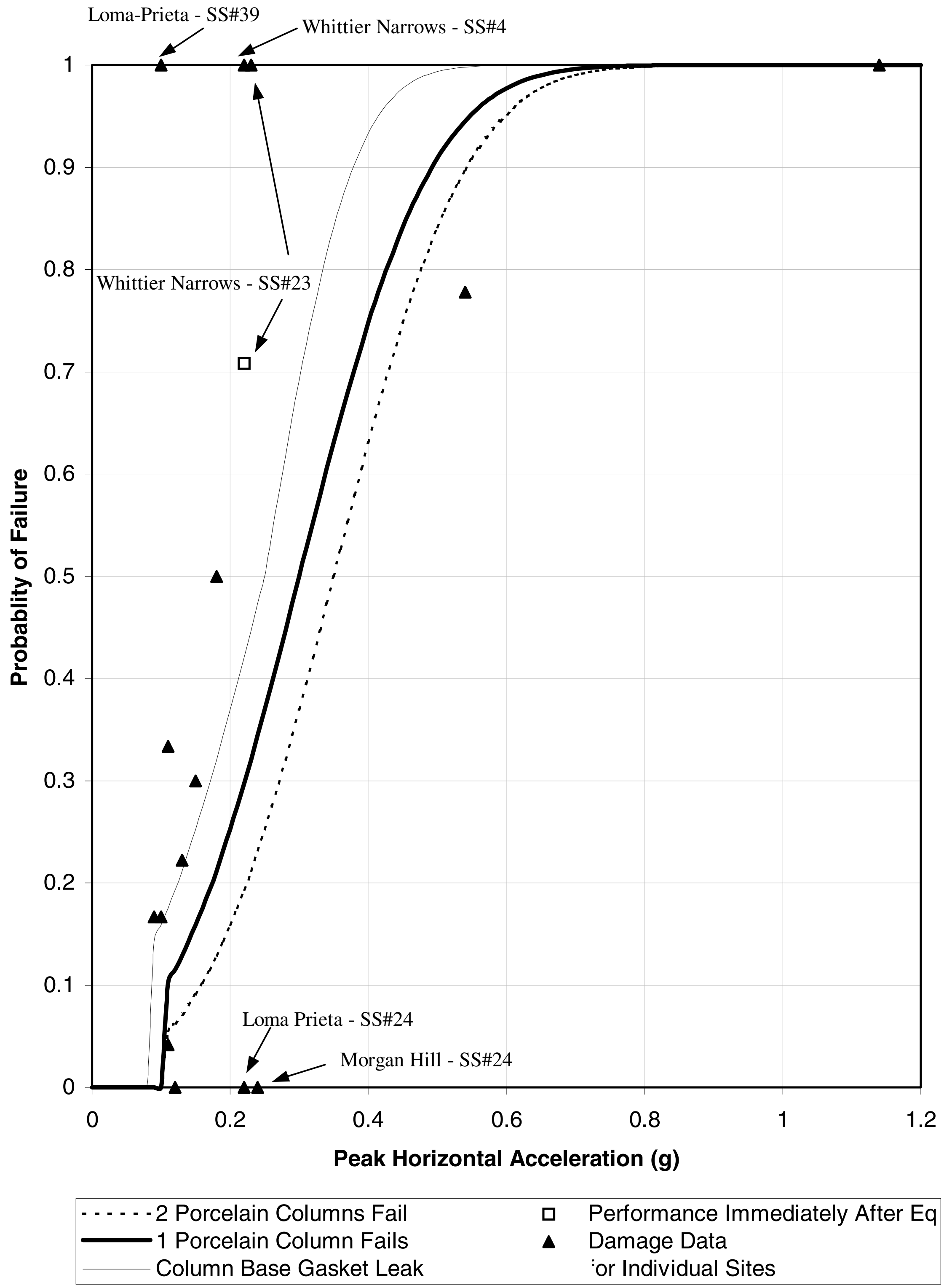

Figure 5.1 Comparison of UWG fragility curves with damage data for 230 kV live tank General Electric ATB4 - ATB6 circuit breakers (CB9). Damage data are plotted for each site.

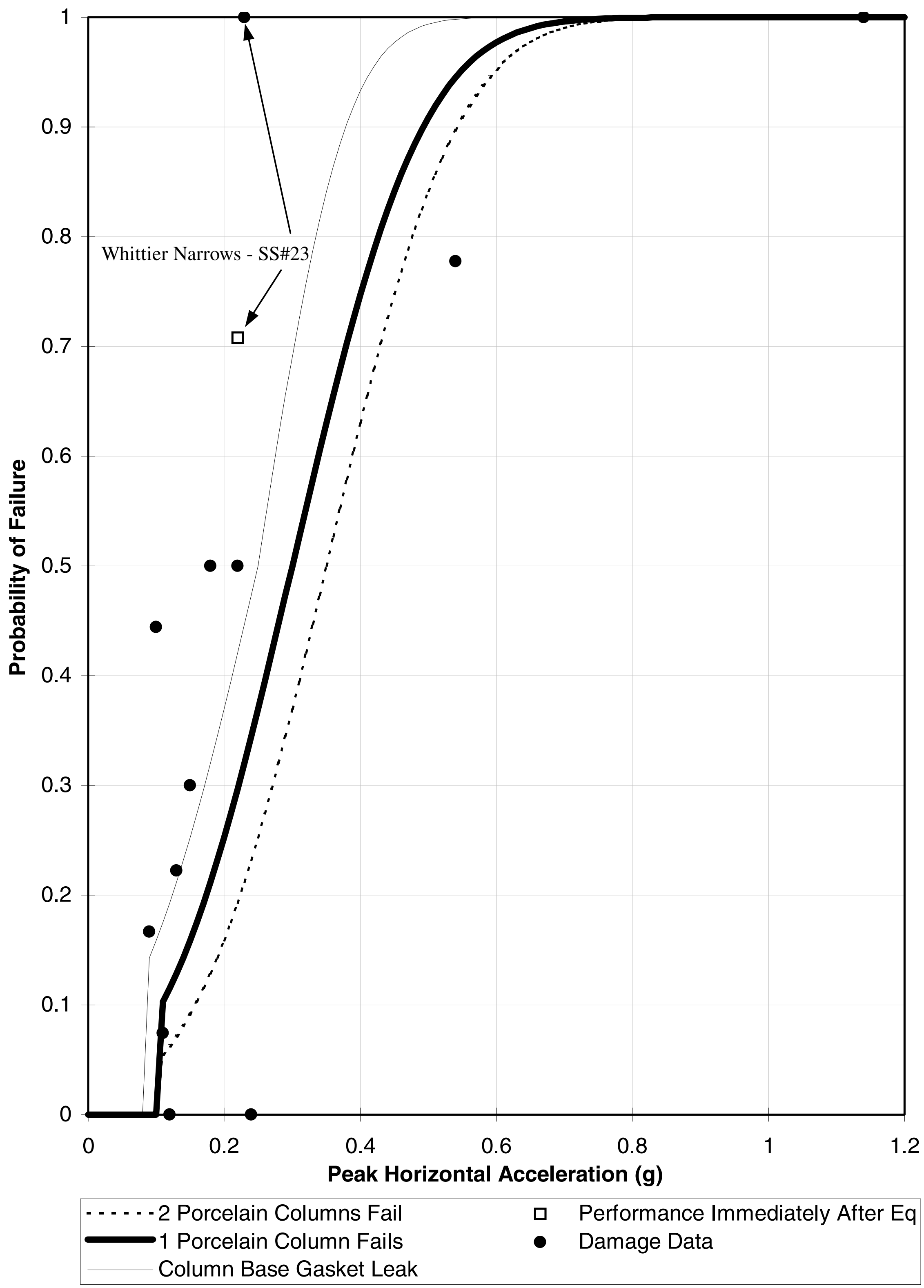

Figure 5.2 Comparison of UWG fragility curves with damage data for 230 kV live tank General Electric ATB4 - ATB6 circuit breakers (CB9). Data for sites with the same PGA are combined and plotted as a single point.

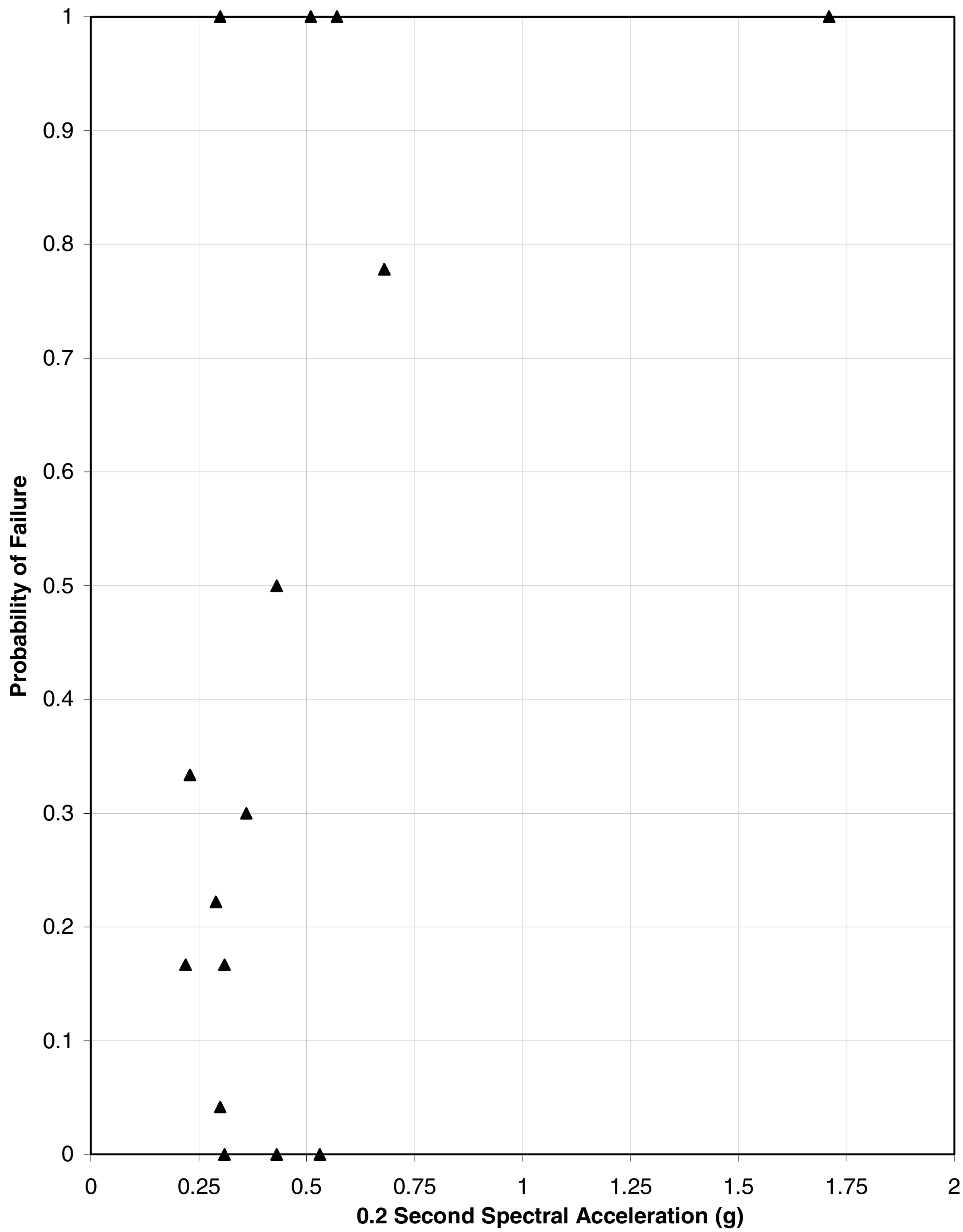

Figure 5.3 Damage data for 230 kV live tank General Electric ATB4 - ATB6 circuit breakers (CB9) for individual sites plotted against 0.2-second spectral acceleration.

Figure 5.4 compares damage data and UWG fragility curves for Westinghouse 500 kV live tank SF6 circuit breakers (CB72). These types of circuit breakers proved to be very vulnerable in the San Fernando earthquake. In an effort to improve performance, CB72 breakers at certain sites were seismically retrofitted using internal prestressing tendons. As can be seen in Figure 5.4, the seismic retrofitting did not always improve the quality of the performance.

In general, the damage data indicate that the UWG fragility curves underestimate the failure rate for this type of equipment. The UWG fragility curves should be adjusted upward to reflect the poor performance of this circuit breaker. In addition, the parameters of the curves should be modified so that the curve representing at least one column failing does not cross over the curves for at least two columns failing.

Figure 5.5 compares damage data with UWG fragility curves for 230 kV and 500 kV lightning arresters. The damage data does not show a clear trend of increased damage probability with increasing PGA. Lightning arresters can be mounted at the top of a transformer, on a boom that is attached to a transformer or on a stand-alone post. Each of these mounts would filter the ground motion differently. The amount of slack on bus drops also affects performance. It is possible that the scatter of the data is a result of not accounting for different mount types and slack. Figure 5.5 does suggest that the minimum level of ground motion needed to trigger damage to a 230 kV lightning arrester is 0.2g rather than the 0.15g defined by the UWG.

Figure 5.6 compares damage data with UWG fragility curves for 230 kV horizontal disconnect switches (DS3). Disconnect switches are difficult to compare because they can be mounted on different types of frames and different types of post insulators, which can have a significant affect on performance.

Several data points on this figure that deviate significantly from the UWG fragility curves deserve additional explanation. While all of the disconnect switches at SS#31 were damaged (solid triangle), 75 phases required realignment only. A second data point plotted for SS#31 (square), represents the damage probability if only those disconnect switch phases that were severely damaged are counted. The damage probability calculated from SS#39 data is based on incomplete information, since there were an unknown number of disconnect switches at the site. This damage probability is unrealistically high, since it does not include all of the undamaged disconnect switches in the ratio of damaged to total switches. Aside from these few anomalous points, the data indicate that for accelerations less than 0.25g this type of equipment has performed well.

Disconnect switches at several substations in the Northridge earthquake, as well as at SS#7 in the North Palm Springs and SS#30 in the Whittier Narrows earthquakes performed particularly well. At SS#44, 24 phases were mounted on heavily braced frames. These had been sine beat tested indicating that they were more modern switches. On average, these performed less well (6 damaged, 18 undamaged) than the phases on less stiff support structures (12 damaged, 120 undamaged). At SS#34, the database indicates that some of the units were seismically qualified. The database provides little insight for the other substations.

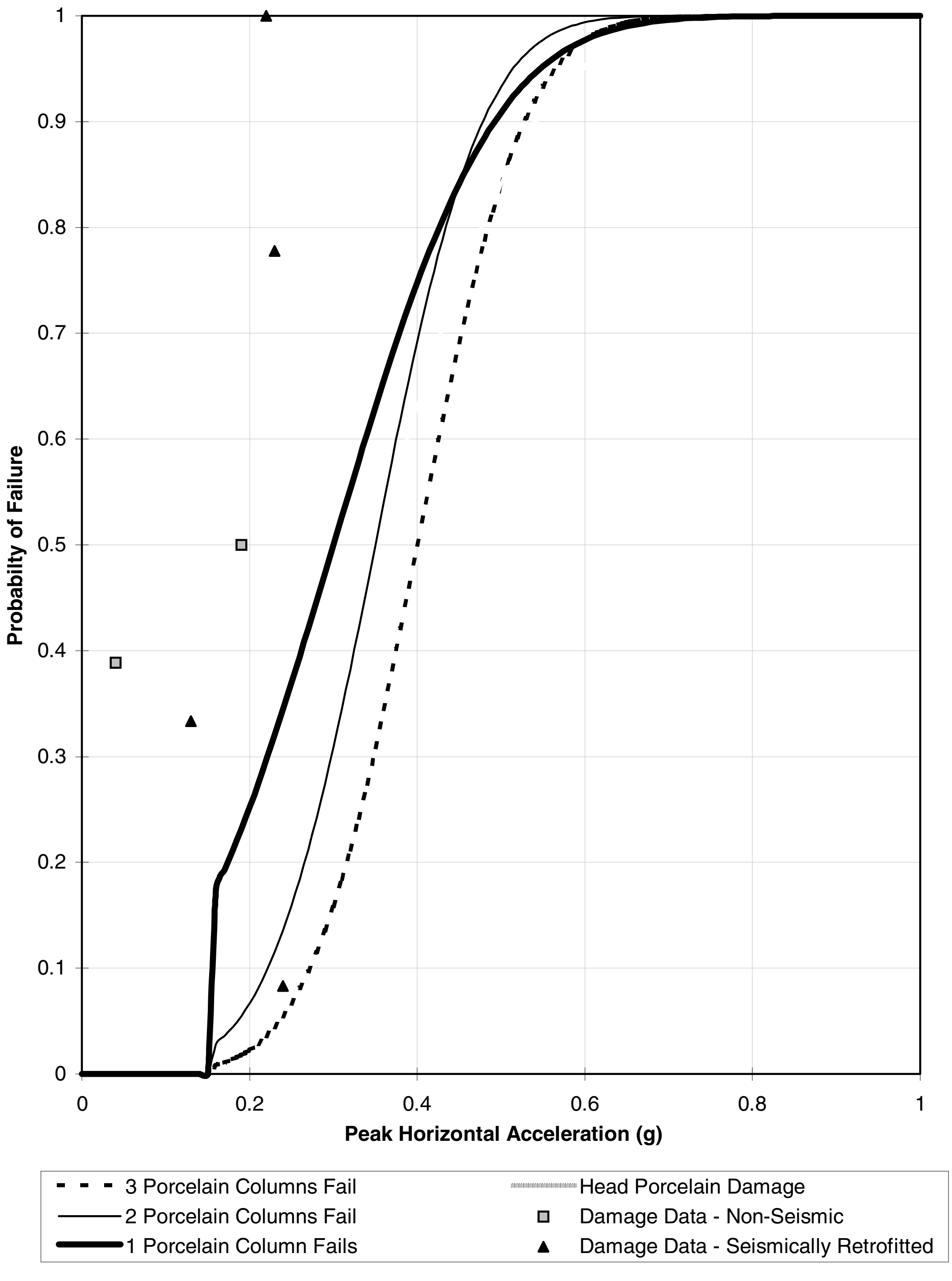

Figure 5.4 Comparison of UWG fragility curves with damage data for 500 kV Westinghouse live tank SF6 circuit breakers (CB72)

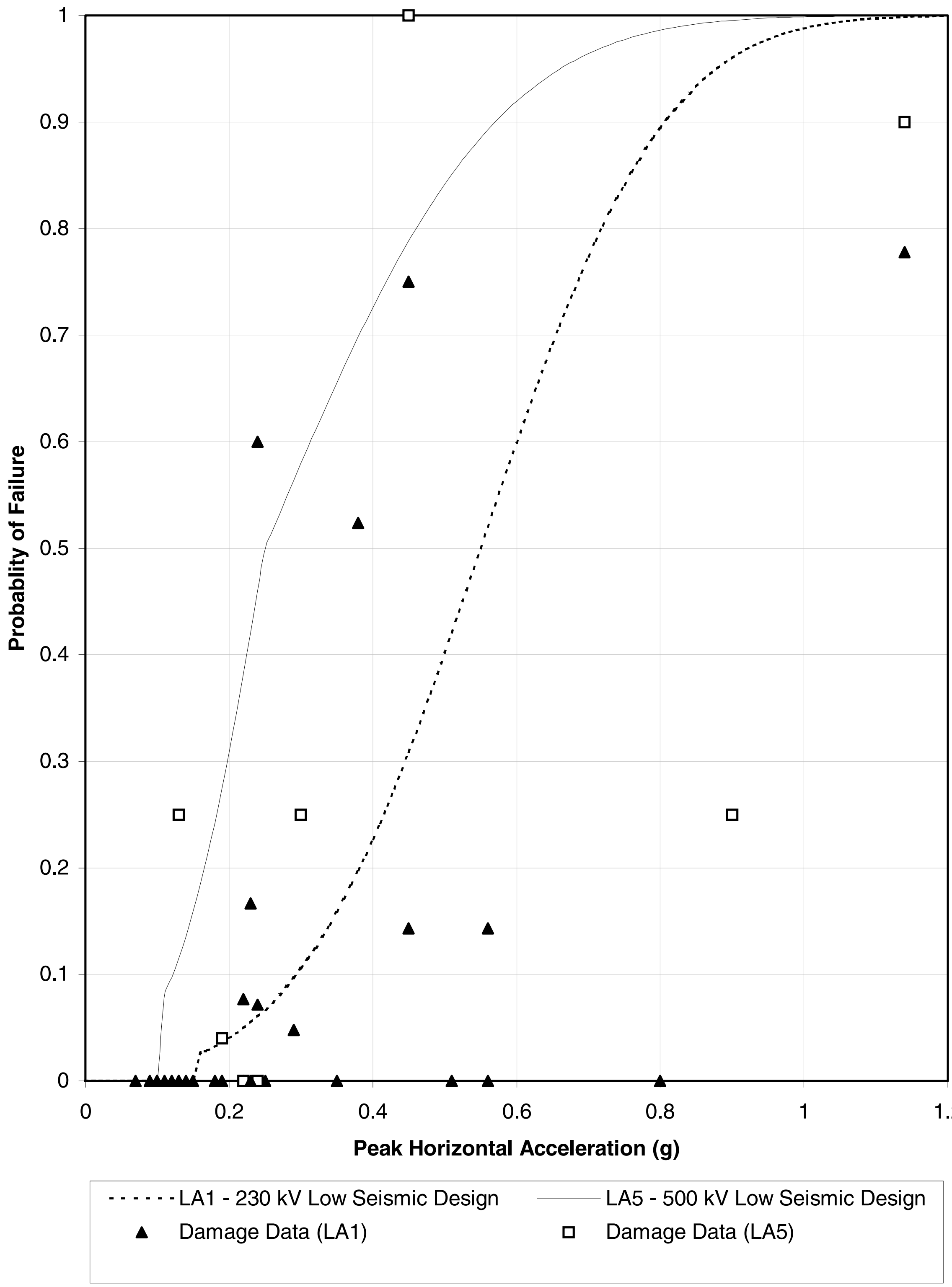

Figure 5.5 Comparison of UWG fragility curves with damage data for 230 kV and 500 kV lightning arresters with low seismic design (LA1 and LA5)

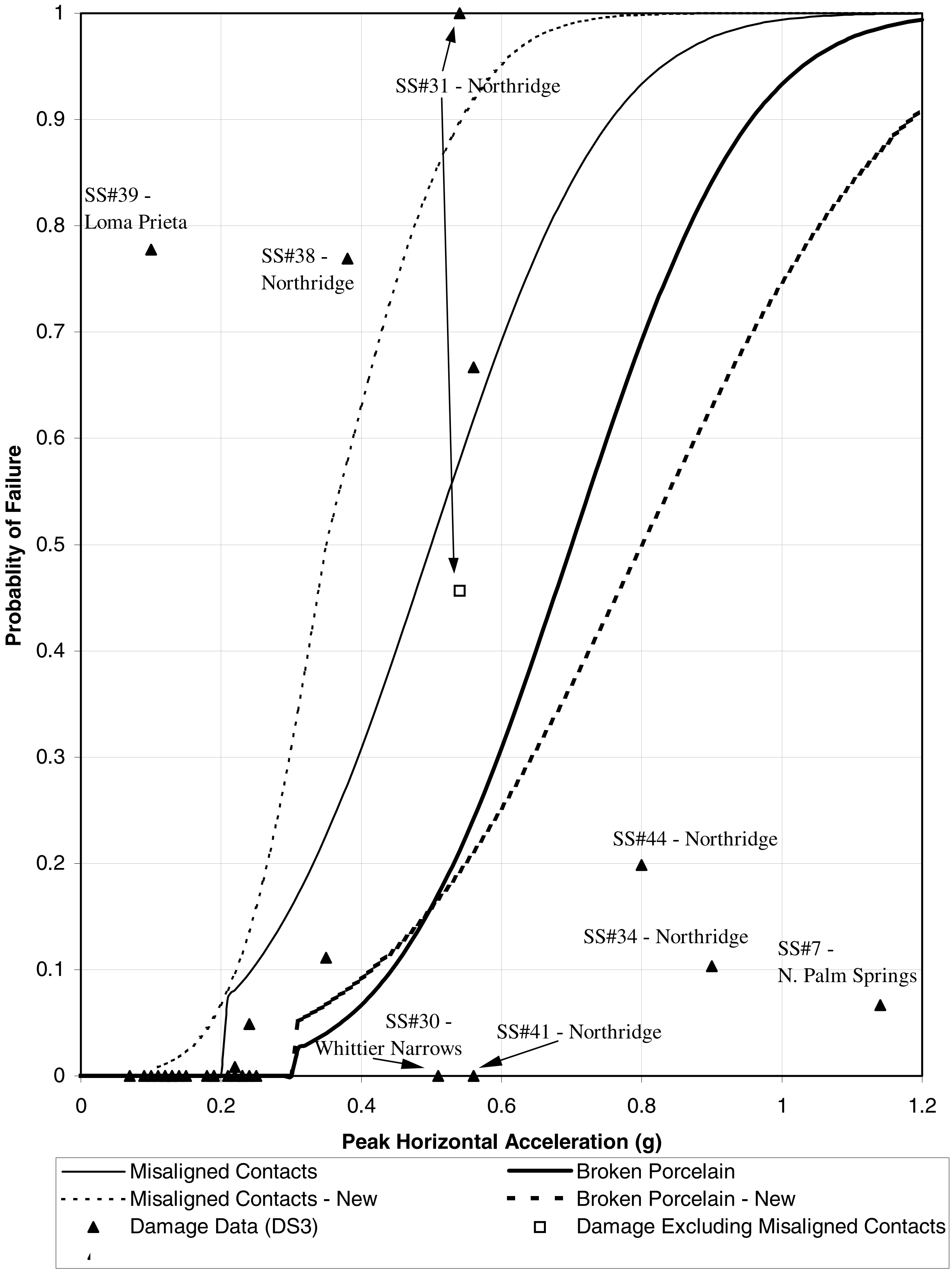

Figure 5.6 Comparison of UWG fragility curves with damage data for 230 kV horizontal disconnect switches (DS3).

Figure 5.7 compares UWG fragility curves with damage data for 500 kV disconnect switches (DS1). There are very few data for this equipment class and no clear trends are evident. At SS#26, the database indicates one of the failures may have been due to equipment interaction. Another failure appears to have been a misalignment in which it is not clear if the equipment remained functional. If both of these failures are removed, the failure probability at SS#26 reduces from 0.60 to 0.55. It remains high with respect to the UWG fragility curves.

Figure 5.8 compares UWG fragility curves with damage data for single-phase 230 kV transformers (TR1). Transformers can have many different configurations and the data in Figure 5.8 do not discriminate between different configurations. Most of the damaged transformers experienced oil leaks due to gasket damage. The data indicate that gasket leaks are occurring at lower PGA's than would be predicted by the UWG fragility curves.

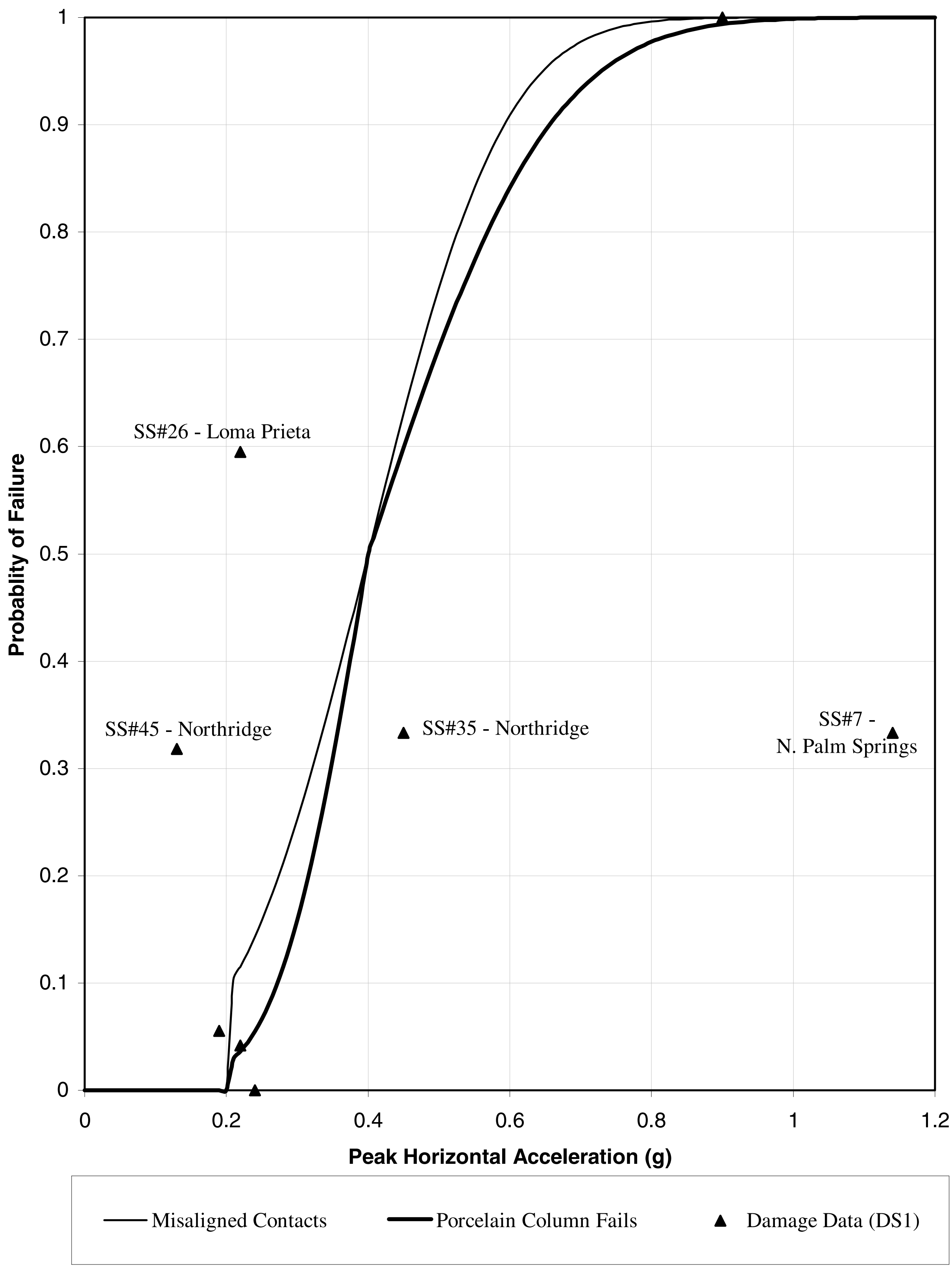

Figure 5.7 Comparison of UWG fragility curves with damage data for 500 Kv disconnect switches (DS1)

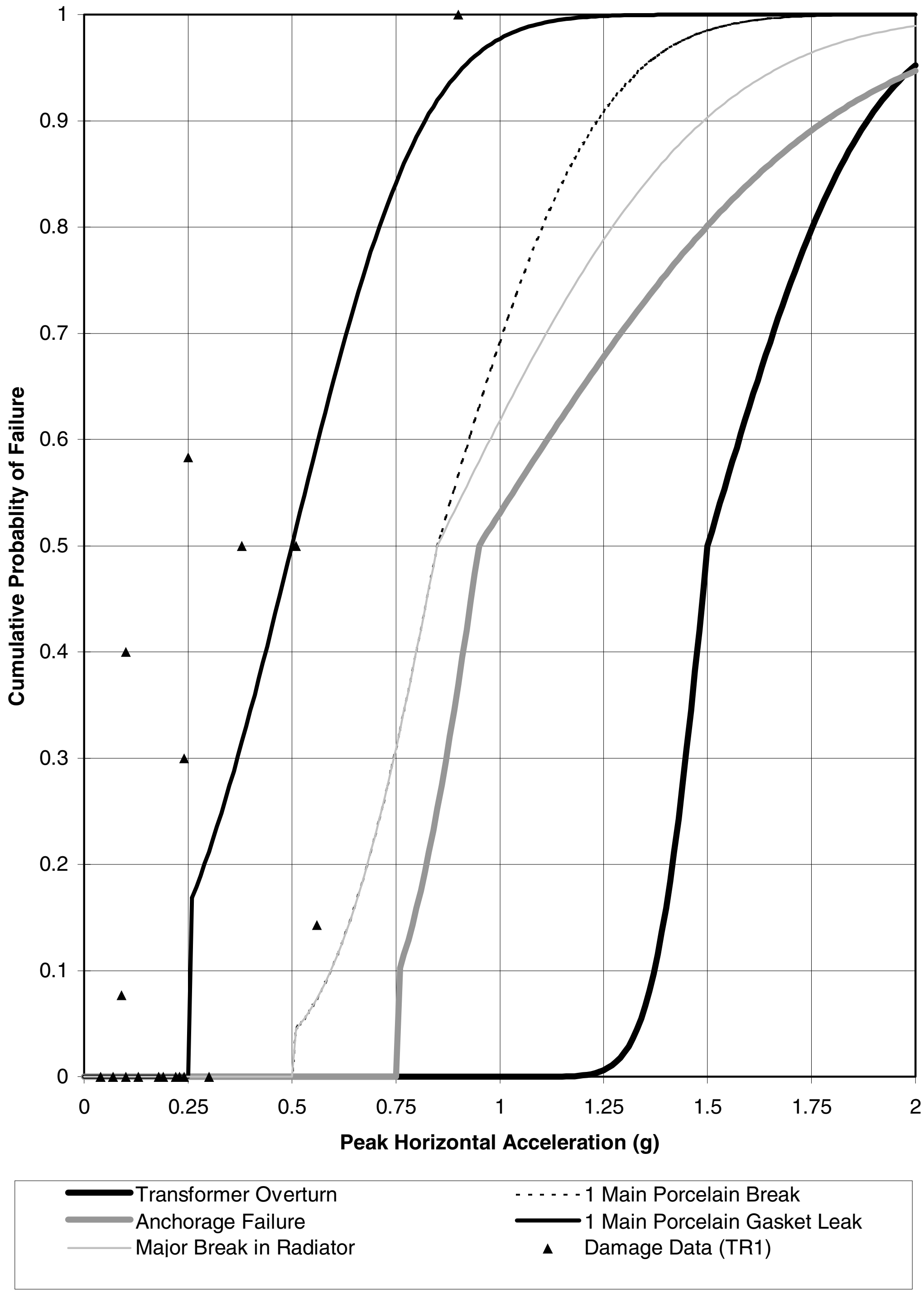

Figure 5.8 Comparison of UWG fragility curves with damage data for single-phase 230 kV transformers (TR1)

6 Future Database Development

The database in its current form provides a useful tool for evaluating damage data from California earthquakes. Several recommendations could be made for improving the database and augmenting its usefulness.

First, a more systematic approach to collecting inventory data would be helpful in performing the analysis. This would minimize some of the uncertainty regarding site conditions and equipment types, models, ages, and quantities. Much of the needed information could be collected prior to the earthquake. It seems that a GIS system would be ideal for storing this type of information. The following would be useful:

- site maps that include soil conditions for the entire site using a standardized classification system
- single line drawings of substation yards
- electronic databases of equipment that include key information outlined in Section 3

Until recently, little to no information regarding undamaged equipment was included in the database. A concerted effort was made to collect this information for the Loma Prieta and Northridge earthquakes. It seems that the inability to quickly access inventory information made this a difficult task requiring multiple visits to a site and lengthy conversations with site personnel. If single line drawings were easily available, electronically if possible, reconnaissance teams could include damage information directly on the drawings. Unique features of the equipment such as unusual support structures, flexible or rigid buses, or retrofits could be easily identified with specific pieces of equipment using equipment designations from the drawings. Similarly, if electronic databases of equipment were easily accessible, the inaccuracies related to equipment make, model, and year could be minimized. It would be helpful if databases included key features such as types of bushings for transformers or seismic qualification information.

A second recommendation involves the re-evaluation of equipment classes. The current UWG classes provide a good foundation for a more refined but systematic classification system. For example, bushing type could be included by using a designation of "p" for porcelain or "c" for composite. The resulting classes for 230 kV single-phase transformers would be TR1p or TR1s. This type of refinement was used for 500 kV Westinghouse live tank SF6 circuit breakers, where the seismically retrofitted circuit breakers were identified as CB72s. The advantage of this type of system is that all equipment of one type (e.g., TR1) can be evaluated together or they can be subdivided according to specific characteristics.

It would be interesting to include data on equipment failure extracted from seismic qualification tests. This would be particularly useful for bushings because damage data include almost no information with respect to bushings.

While the database has a field to include the failure mode, this field is often blank. A more systematic approach to defining and recording the failure modes is needed if realistic comparisons with the UWG fragility curves are to be made.

The current format of the database with 68 columns of data makes it somewhat awkward to use. Since Excel is not a dedicated database manager, performing queries is difficult. It may be worthwhile to consider converting the Excel file to a database system that is supported by Pacific Gas and Electric. When doing this it may be useful to rethink the organization of the database somewhat.

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