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AN ANALYSIS OF FIRE SPRINKLER SYSTEM FAILURES DURING THE NORTHRIDGE EARTHQUAKE AND COMPARISON WITH THE SEISMIC DESIGN STANDARD FOR THESE SYSTEMS

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SUMMARY

This study analyzes fire sprinkler system failure data from the Northridge Earthquake and compares the findings with the primary seismic design standard applied to sprinkler systems, National Fire Protection Association (NFPA) 13, Installation of Sprinkler Systems. The intent of this paper is not to perform a rigorous examination of the data as compared to NFPA 13 requirements, but to instead present the applicability of this type of loss data when quantifying the seismic design requirements applicable to fire sprinkler systems.

INTRODUCTION

Fire sprinkler systems have been installed in seismically active areas in the United States for the past 100 years [3]. The first seismic design requirements were incorporated into the primary engineering standard pertaining to these systems in 1947 [1]. Dating back to the 1933 Long Beach earthquake, seismic events have caused documented damage to sprinkler systems failures noted in several subsequent post earthquake studies [5].

Typical damage to sprinkler systems noted includes broken sprinkler heads, piping, and fittings that occurs when system components either come in contact with architectural and structural elements or there is a failure at a fitting due to impact or seismic forces [1].

Both property damage and life safety issues are related to damage to sprinkler systems. From a life safety perspective the reduction in the level of fire protection is a major concern. Fortunately, this facet of the problem has to date not resulted in fires causing large property loss or loss of life. Historically the primary impact resulting from sprinkler system failures in earthquakes is water damage that ensues when system components are damaged and water is subsequently released into the facility.

This was a major component of the total losses paid out by commercial insurance companies following the Northridge Earthquake in 1994. Many commercial insurers have reported that they paid out more losses due to sprinkler leakage than earthquake shake damage due to the extent of damage and the manner in which the coverage is often written (low deductibles and high limits of coverage). Insurers refer to this coverage and source of loss as earthquake sprinkler leakage or EQSL. By addressing the issue of sprinkler

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system functionality following a seismic event encapsulates the property damage (fire and water), business continuation, and life safety components of the problem.

Although sprinkler system damage has been noted over the past 70 plus years, no detailed engineering damage data has been collected and analyzed pertaining to sprinkler systems to date that could be used as an aid to quantify the need of including additional design requirements to resist seismic forces. This study pulls together a body of engineering damage data from proprietary and publicly available sources in an effort to highlight the insight that can be gained into the effectiveness of this type of data in the code making process.

HISTORIC FIRE SPRINKLER SYSTEM SEISMIC PERFORMANCE

History of fire sprinkler systems

Automatic fire sprinkler systems were initially installed in the United States in primarily high fire hazard industrial occupancies in the early 1900s [3]. This includes seismically active areas. Over the years the use of sprinkler systems has spread dramatically to include occupancy types that have a high occupancy load or occupants that may be impaired for various reasons (hospitals, hotels, nursing homes, etc.). New construction of office buildings, retail stores, hospitals, assembly areas, etc. are quite commonly required to install automatic fire sprinkler systems.

Sprinkler system damage due to earthquakes

The first earthquake noted with documented damage to fire sprinkler systems was the 1933 Long Beach earthquake, which struck the Los Angeles area [5]. This was also the first major earthquake to strike an area with an appreciable number of fire sprinkler systems (approximately 500 in the affected area). The Long Beach earthquake occurred prior to any seismic design requirements being included in the primary design standard pertaining to sprinkler systems, National Board of Fire Underwriters (NBFU) standard 13. This standard is now referred to as National Fire Protection Association (NFPA) 13, Standard for the Installation of Sprinkler Systems. The first reference to protection against earthquake damage was inserted into this standard in 1947 and provided a minimal amount of design guidance [1].

Table 1 provides a summary of fire sprinkler system damage observations for several earthquake events:

Earthquake Event	Fire Sprinkler System Damage Observations
Long Beach, 1933	Of 150 sprinkler systems in the area that suffered heavy structural damage 40% were undamaged, 40% were suffered minor damage, and 20% suffered serious damage. Another 350 sprinkler systems were located in the quake area, but evidently were not damaged due to a lower seismic intensity. No information on the extent of water damage to contents (i.e. EQSL loss) was included in published reports for this event [5].
Kern County, 1952	An estimated 26 sprinkler systems were located in heavily shaken areas. All 26 systems were reportedly braced in accordance with the current edition of NFPA 13 (1951 edition). One system was damaged when bracing pulled away from its supports. There was no leakage [5].
Alaskan, 1964	It is estimated that 24 sprinkler systems were located in Anchorage & adjacent Spenard at the time of this event. Damage inflicted on these systems included 2 that were destroyed due to a partial to total building collapse, 1 that was damaged when the building was severely damaged, and 2 that were slightly damaged by a falling chimney & dropped rear balcony. Another 2 systems were out of service due

	to the city water being out.[5]
San Fernando, 1971	Of the 973 sprinkler system protected facilities located in the affected area 38 suffered slight to severe damage of which 28 systems had a leakage loss. A separate table detailing the damage to 68 sprinkler systems surveyed by the Pacific Fire Rating Bureau is included in this document. This was the first earthquake event during which EQSL occurrences and the corresponding level of leakage damage was documented to any extent. [5]
Loma Prieta, 1989	No reliable statistics are available for the total number of EQSL occurrences during this event. The primarily industrial insurer, FM Global had 12 claims total, which is a small amount for such a large property carrier [2]. A paper published in ATC-29 states that failures of installed systems ranged between 5% to 10% in areas with MMI intensities of approximately of VII to VIII. This same paper stated that system performance was comparable to the 1971 San Fernando EQ [3].
Northridge, 1994	The Northridge earthquake was by far the largest sprinkler system damage event to date. A NIST study on sprinkler system performance stated that 1% to 2% of sprinkler systems in the affected area were damaged during this event. No estimates of the total number of sprinkler system failures that occurred are available, but the overall amount of damage was clearly substantial. Occupancy types hardest hit included retail, office buildings, and hospitals [1].
Kobe, 1995	Not many sprinkler system protected buildings are in Japan. There were EQSL losses primarily in industrial occupancies.
Chi-Chi, 1999	Not many sprinkler system protected buildings are in Taiwan. Sprinkler system failures noted were in industrial occupancies. Some specific information is available, but no detailed loss data.
Nisqually, 2001	Sprinkler system failures were pretty common in this event, but most were small due to the level of shaking experienced.

Table 1
Historic Earthquake Events Resulting in Sprinkler System Damage Summary

In addition, the Pacific Fire Rating Bureau captured sprinkler system damage information as displayed in Table 2 following the San Fernando Earthquake (1971):

Damage Level	**Buildings Damaged**		**Sprinkler System Damaged**		**Sprinkler Leakage Loss**	
	Number	**%**	**Number**	**%**	**Number**	**%**
None	6	9	30	44	40	59
Slight	25	37	16	24	12	18
Moderate	13	19	9	13	7	10
Severe	24	35	13	19	9	13
Totals	68	100	68	100	68	100

Table 2
San Fernando Earthquake Sprinkler System Damage Summary [5]

Table 3 was compiled based on reports following several earthquake events during which sprinkler systems were damaged and the number of fire sprinkler systems located in the area affected was known.

Earthquake Event	Magnitude	Estimated Percent of Sprinkler Systems Damaged[1]	Total Systems in Area Affected
1933, Long Beach	6.3	18%	500
1952, Kern County	7.7	3.8%	26
1964, Alaskan	8.4	21%	24
1971, San Fernando	6.4	3.9%	973

1. Prior to the 1971 San Fernando EQ data on leakage occurrence was not documented only damage to sprinkler systems. This distinction needs to be clear since damage to sprinkler systems does not always result in sprinkler leakage damage or sprinkler system impairment (i.e. underground main damage, bracing damage, riser only damage, etc.).

Table 3
Comparison of Sprinkler Systems Damage for Several Earthquake Events

From the historic damage information presented in the preceding three tables it is clear that fire sprinkler systems are susceptible to seismic damage, but what is not clear are the critical issues that drive the level of susceptibility and at what seismic intensity damage is incurred.

FIRE SPRINKLER SYSTEM SEISMIC DAMAGE ENGINEERING DATA

Damage data specifics

As indicated in Table 1, the Northridge Earthquake of 1994 had by far the most fire sprinkler systems damaged of any earthquake to date. Although no overarching damage data is available for this event that includes the total number of systems damaged, there is damage data available that can be utilized as an aid in determining the key factors that drive seismic performance of fire sprinkler systems.

Sprinkler system component damage data was collected from a variety of proprietary and publicly available resources in an effort to better identify the key failure traits of fire sprinkler systems. A commercial insurer established the original data format for the database and collected a majority of the data through field surveys performed just after the event. Additional data was retrieved from various publicly available reports with detailed damage information on specific facilities [4], [8].

All of the records in the database assembled represent an individual facility that had a failure of their fire sprinkler system during the Northridge Earthquake (1994). A total of 119 facilities are included in the database. This is far from the total amount of facilities that sprinkler system damage during this event. The data includes only occupancies that had drop down ceiling systems, which was a common facility trait for sprinkler system failures during the Northridge event.

The Modified Mercalli Intensity (MMI) estimated by the USGS at the zip code level is included in the database to better analyze the level of intensity at which specific data fields are populated as being involved with the sprinkler system failure.

Ultimately this data set is limited in size and detail however, it provides engineering insight into sprinkler system failures in seismic events. Perhaps more importantly an analysis of the data emphasizes how this type of engineering data can aid in quantifying key failure issues, which can lead to better-informed design standard development.

The following table provides information on the data fields included in the data set:

Data Field	Description
Occupancy	Occupancy type description broken out into Airport, Hospital, Light Industrial, Office, & Retail
Zip Code	Zip code for the building
MMI	Modified Mercalli Intensity for the zip code as determined from the USGS map for the Northridge event.
Construction	Construction type description broken down into five types: Concrete, Frame, Steel Frame, Tilt-up, and Unknown
Age	Age of building ranging from 1940-1993.
Sprinkler Heads	Physical damage to sprinkler heads.
Mechanical Fittings	Failure of a mechanical fitting(s) on the sprinkler system.
Threaded Fittings	Failure of a threaded fitting(s) on the sprinkler system.
Contact Building	System component failed after coming into contact with building components (except the drop down ceiling system).
Contact Ceiling	System component failed due to coming into contact with the drop down ceiling system.
>4' Drops	Failure of pipe drops that are in excess of 4 feet in length.
Armovers	Piping failure at an armover section.
No Wrap-Around	Lack of wrap-around on pipe bracing resulted in piping failure.
Longitudinal Bracing	Lack of longitudinal bracing was involved with the failure.
Lateral Bracing	Lack of lateral bracing was involved with the failure.
No Retainer	No retaining strap on a C clamp supporting sprinkler system piping.
Powder Driven Fastener	Piping was anchored with powder driven fasteners, which failed.

Table 4
Northridge Earthquake Sprinkler System Damage Data Field Description

It should be noted that multiple failure fields are often populated for the same building. This intuitively makes sense since several distinct traits can all be involved in ultimately the failure of the fire sprinkler system. This is especially true in a large facility with multiple sprinkler systems. For example, if sprinkler heads are damaged due to a lack of lateral bracing after coming into contact with the building then 3 failure fields can be populated for the same event; Sprinkler Heads, Lateral Bracing, and Contact Building.

Fire Sprinkler component damage perspectives

To gain insight into fire sprinkler component failures various views of the engineering data were created. The intent is to identify the leading failure issues as represented by fields in the database. The data fields have been sorted by MMI to pinpoint the sensitivity by earthquake intensity level. Figure 1 displays the MMI by zip code as estimated by the USGS for the Northridge Earthquake.

It is important to note that MMI ≤ 6 covers a very large area and therefore a large exposure of sprinkler system protected facilities, while MMI 9 covers quite a small area. These factors tend to skew the results.

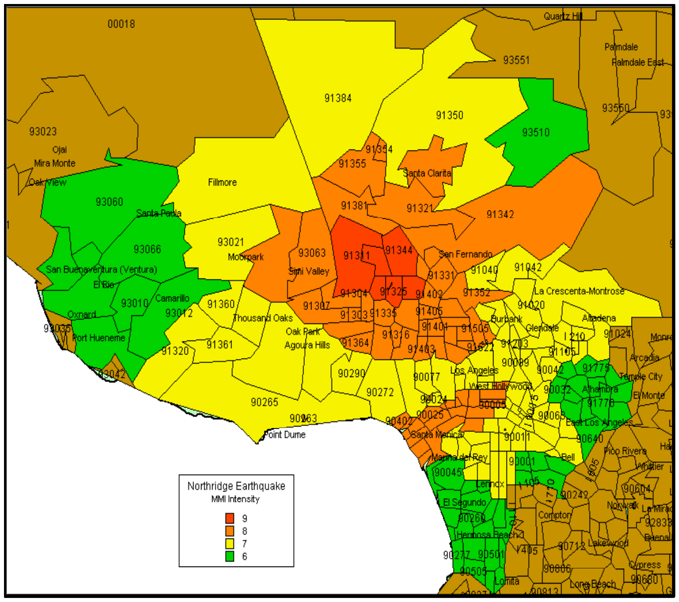

Figure 1
Northridge MMI estimates by Zip Code

Sensitivity to damage by MMI
In Figure 2 the percentage of the total entries for each MMI by all entries is presented. So for each data field the percentage for MMI ≤6 up to 9 adds up to 100% of the total entries for the data field.

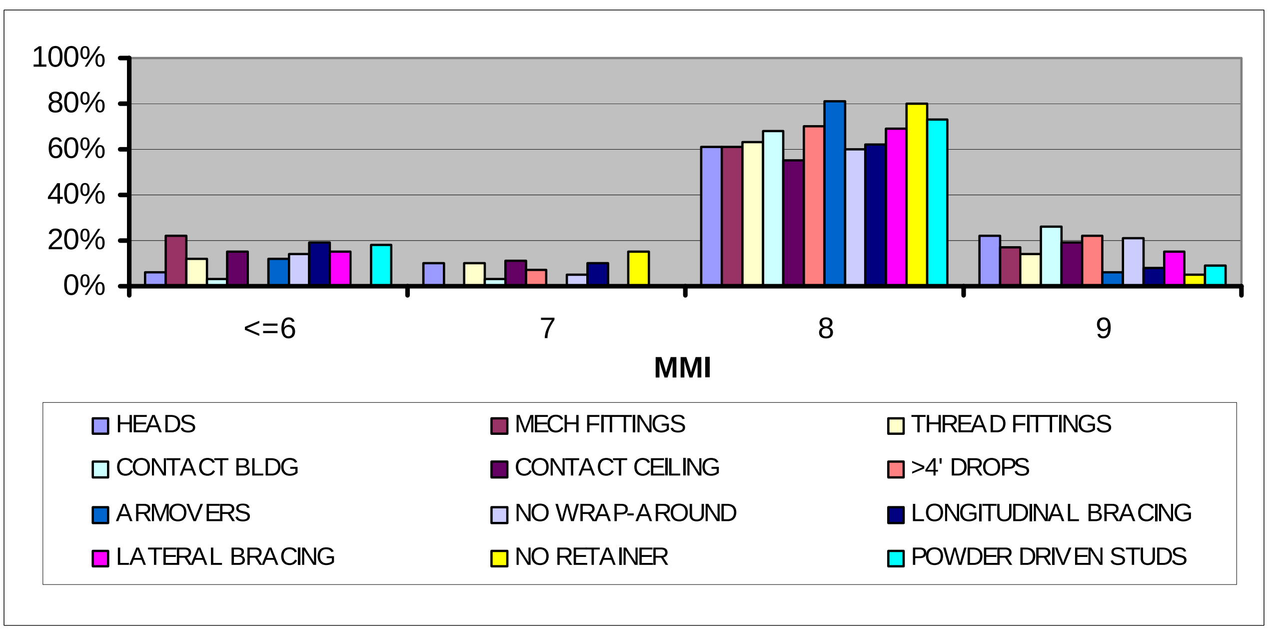

Figure 2
Percent of total data field entries at each MMI

This view of the data set highlights that the largest percentage of data entries for all data fields occurs at MMI 8. It also points out that this is true for essentially all of the data fields collected. Although this data set is too small to be considered statistically representative of the entire distribution of fire sprinkler systems in the geographic area impacted by the earthquake it is clear from the data that there is an appreciable change in the failure rate at a damage level of MMI 8.

At MMI 9 there is a drop off in the percentage of entries, which is likely due less to better performance of systems and more to the smaller geographic area that experienced this level of intensity as displayed in Figure 1.

Data field population by MMI
Figure 3 provides some insight into the MMI at which each data field is populated as involved in the fire sprinkler system failure. This chart displays the percentage of facilities exposed to each MMI that had each data field populated. For example, at MMI 8 there were 75 facilities in the database of which 40% had damage to sprinkler heads populated.

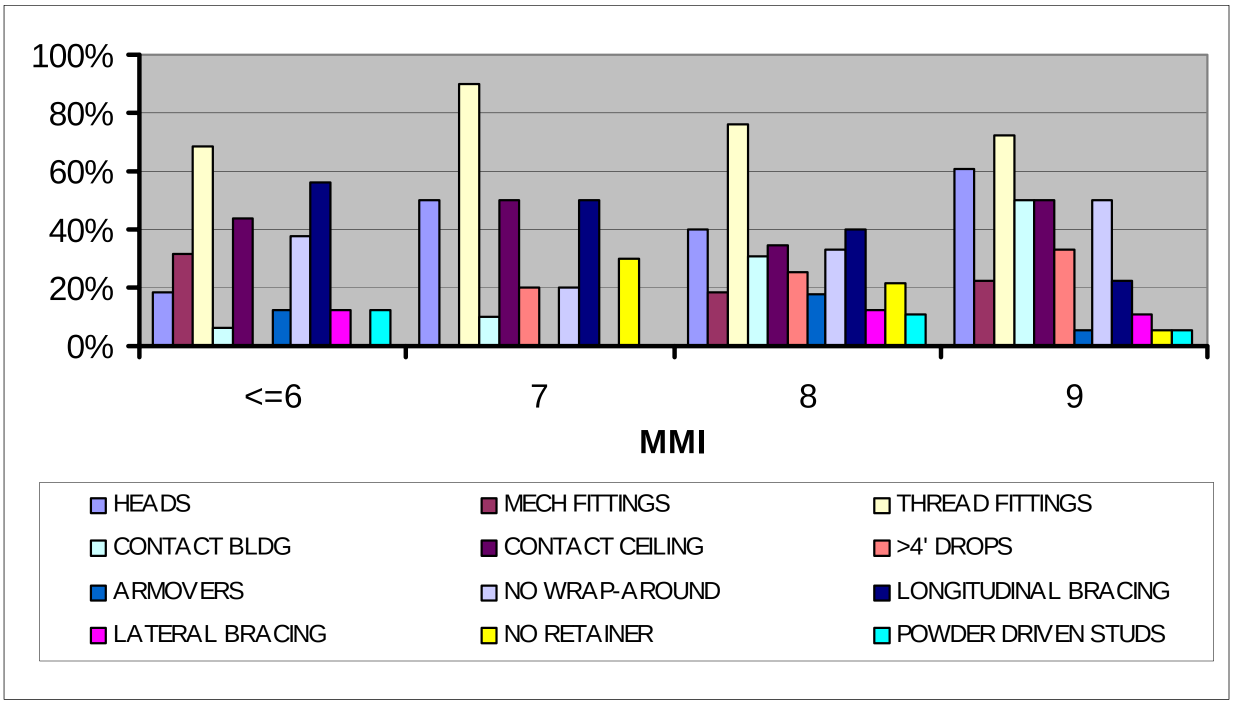

Figure 3
Percent of total data field entries at each MMI

Figure 3 highlights the relationship of certain data fields at various intensities to the failure of the fire sprinkler system. From a review of this figure the following three data fields are noted to be consistently populated at all intensities.

1. Thread Fittings
2. Longitudinal Bracing
3. Contact Ceiling

The remainder of this paper will focus on these three data fields with respect to how NFPA 13 addresses each.

NFPA 13 REQUIREMENTS RELATED TO KEY DATA FIELDS IDENTIFIED

Threaded Fittings

Failure at threaded fittings is somewhat of a misleading data field since the majority of sprinkler system fittings in the built environment are threaded. For this reason when sprinkler systems fail in an earthquake at a fitting the failure will typically be associated with a threaded fitting.

Newer sprinkler systems have a higher percentage of mechanical fittings, but threaded fittings are still quite common. Mechanical fittings is also one of the more frequently populated data fields as shown in Figure 3 at each earthquake intensity level. If a serious discrepancy between the two was noted in the date the issue would merit more in depth study into the reasons why. NFPA 13 does not treat threaded fittings any differently than mechanical fittings from a seismic design perspective.

It should also be noted that research is currently underway at the University of Southern California into the failure of sprinkler system components during seismic events including threaded fittings. This research could lead to additional conclusions regarding the susceptibility of different types of fittings to seismic damage.

Longitudinal Bracing

Longitudinal bracing is refers to the bracing of piping from moving in a direction parallel to the pipe itself. This type of bracing has been required in NFPA 13 for sprinkler mains since the 1951 edition of the standard, which required a longitudinal brace for each feed and cross main. Unfortunately, this requirement could be met in many cases by installing a four way brace at the top of the system riser as shown in Figure 4 [7].

Figure 4
Four-way brace at a sprinkler system riser

In the 1987 edition of NFPA 13 the requirement was supplemented to require longitudinal braces spaced at a maximum of 80 feet for mains thereby removing the single brace on the system possibility in all but the very smallest systems. The average facility age in the database is 1972 so it is evident that the 1987 version of the standard is not represented in the data. In fact less than 8% of the buildings in the database where constructed after 1987. It is clear that the technical committee took action on an issue that the data developed in this report from the Northridge event further emphasizes is a serious issue in seismic events.

To further examine the impact and adequacy of the changes to the standard relative to longitudinal bracing requirements additional data is needed on sprinkler protected facilities constructed in 1989 and later, which would allow for time to adopt the 1987 standard requirements. These damage statistics can be compared to the pre 1989 facilities to better determine the effectiveness.

Contact Ceiling

Sprinkler heads being damaged after coming into contact with ceiling systems has been noted in several previous earthquakes, but the extent of damage with this issue as a contributing factor has never been as apparent as in the Northridge earthquake.

The common mode of failure in this case involves the breaking of threads at the top of sprinkler drops to sprinklers penetrating a substantial ceiling (fire rated or decorative metal ceilings being prime examples). There were also many cases where sprinkler heads were pulled up through the ceiling and then slammed back down. In these cases the sprinkler heads often impacted ceiling materials when they came back down resulting in sprinkler head damage and failures at fittings [7]. As previously indicated, this issue is especially troublesome for fire rated and decorative metal ceiling systems since they offer more resistance to the movement of the sprinkler piping, but has also been noted in standard T-bar drop down ceiling systems to a lesser extent as shown below in Figure 5.

Figure 5
Drop-down ceiling contact resulting in fire sprinkler system damage
Northridge earthquake 1994

In the 1983 version of NFPA 13 language was added that required systems installed in a fashion to minimize or prevent pipe breakage during seismic events, but nothing specific to ceiling systems was referenced. The standard was tightened in the 1989 version by requiring lateral bracing of branch lines down to 2 ½” piping. The language was firmed up a bit more in the 1991 version to specifically state that a form of bracing was required “where upward or lateral movement of sprinklers would result in an impact against the building structure, equipment, or finish materials" and that these braces should not exceed 30 feet on center.

At present there is no requirement in NFPA 13 that ceiling and sprinkler systems be braced as a unit, which would minimize the extent of differential movement. However, following the Northridge event there was considerable debate with regard to this issue as to how the standard needed to address differential movement [1]. The bracing the systems as a unit concept was one of the proposals placed on the table for consideration. The biggest proponents were commercial insurers that paid substantial EQSL losses. Loss estimates for this coverage for the Northridge event are in the hundreds of millions. Opponents of the bracing as a unit approach are concerned with both the cost and complexity of designing this type of system.

Ultimately no additional requirements were implemented related to this issue in the subsequent release of the standard in 1996. The committee determined that the existing provisions adequately address the problem.

Since the 1991 version of the was in place only 3 years prior to the earthquake event there were few systems exposed to the earthquake designed to this standard [6]. In fact, there are only four facilities in the database potentially designed to this version of the standard, which is clearly not enough data points to make an argument for or against additional requirements. Gathering more data on this issue could clearly help build a case for or against additional requirements related to this issue.

CONCLUSIONS

From the information presented in this paper it is clear that seismic damage to fire sprinkler systems is not a trivial issue from both a financial loss and life safety perspective.

Detailed engineering data such as that assembled and presented at a high level can clearly add insight into critical issues involved with the failure of sprinkler systems in earthquake events. The need and effect of engineering criteria changes implemented in dominant design standards such as NFPA 13.

Although this paper sheds some light on the effectiveness of this type of data it is clear that considerably more data is needed in order to query as many combinations of factors as possible (age, occupancy, earthquake intensity, construction type, contact ceiling, longitudinal bracing, etc.). In addition, expanding the scope of the data to include sprinkler system protected buildings that did not suffer damage to their systems during an earthquake would be useful to better ascertain what is going right as well.

Ultimately there is considerable power in detailed damage data that if collected and applied appropriately can aid in the standard development.

REFERENCES

1. Fleming R., "Analysis of fire sprinkler systems performance in the Northridge Earthquake", National Institute of Standards and Technology, NIST-GCR-98-736, pages 2-44.
2. Fleming R., "Lessons from the Loma Prieta Earthquake", Sprinkler Quarterly, Summer 1990, 32-33.
3. Harris S., "Fire Protection Systems: Post-Earthquake Experience & Reliability", ATC-29 Seminar Technical Papers, 192-194.

4. Ayres & Ezer Associates Consulting Engineers, “Northridge Earthquake Hospital Water Damage Study”, Office of Statewide Health Planning & Development, Division of Facilities Development, April 1996, 25-85.
5. Steinbrugge K., “Earthquakes, Volcanoes, and Tsunamis An Anatomy of Hazards”, Skandia America Group, 144-146.
6. Earhquake Spectra, “Northridge Earthquake Reconaissance Report, Vol. 1, 464-467.
7. R. Fleming, “Sprinkler System Performance in the Northridge Earthquake”, Sprinkler Quarterly, Spring 1994, 20-21.
8. S. Hart, “Northridge Earthquake”, Fire Sprinkler Advisory Board of Southern California, 15-20, Appendix A.