0054

CHANGING PERCEPTIONS OF THE EXTENT OF DAMAGE TO WELDED STEEL MOMENT FRAMES IN THE NORTHRIDGE EARTHQUAKE

Terrence F PARET[1] And Mourad R ATTALLA[2]

SUMMARY

Studies of the post-Northridge inspection reports of welded steel moment frame buildings in Los Angeles are described. The studies show that the distribution of W1 damage as defined by SAC is inconsistent with the distribution of all other non-W1 fracture categories, which strongly suggest that W1's are unrelated to earthquake shaking. With this understanding, an evaluation of the inspection reports reveals that relatively few buildings experienced significant fracturing with approximately 90% of all reported non-W1 occurring in just 27 buildings. The inspection reports also show that visual inspection is a more effective and less expensive method for post-earthquake damage assessment than is ultrasonic inspection.

INTRODUCTION

Approximately one year after the Northridge earthquake, the City of Los Angeles adopted Ordinance #170406 which mandated that welded steel moment frames within certain geographical regions under the City's jurisdiction be inspected for earthquake damage and which caused reports to be generated for submission to the City of Los Angeles Department of Building and Safety. The geographical regions comprised much of the San Fernando Valley and an area generally described as portions of West Los Angeles. Approximately 250 welded steel frame buildings were noticed under the ordinance, and 209 of the reports generated by the mandated inspections were made available for this study. The 209 buildings described by these reports are believed to be representative of the City of Los Angeles sample as a whole.

The reports were prepared by a number of engineering firms on the basis of inspections performed by different testing agencies. Consistency between these reports, both of information reported and of the engineering interpretations of W1 type conditions [SAC, 1995] reported by the inspection agency is largely absent, though nearly all the inspections generally followed SAC inspection procedures. Therefore, to impose consistency, the studies herein relied only on the raw data reported for each connection by the testing agencies and all the available inspection data sheets were reviewed and interpreted by one individual. These studies include an evaluation of the relative distributions of W1 conditions and non-W1 conditions found in torsionally regular buildings in the San Fernando Valley; an evaluation of the relative distributions of W1 conditions and non-W1 conditions found in all buildings in the City of Los Angeles files; and an evaluation of the adequacy and cost-effectiveness of post-earthquake visual inspection versus the adequacy and cost-effectiveness of post-earthquake ultrasonic (UT) inspection.

DISTRIBUTION OF CONDITIONS FOUND IN TORSIONALLY REGULAR BUILDINGS IN THE SAN FERNANDO VALLEY

Within the San Fernando Valley, the ground motions during the Northridge earthquake were more strongly directed along a north-south axis. For example, a recent study catalogued buildings in the San Fernando Valley

[1] *Wiss, Janney, Elstner Associates, Inc., 2200 Powell St., #925, Emeryville, CA 94608, 510-428-2907, e-mail tparet@wje.com*
[2] *Wiss, Janney, Elstner Associates, Inc., 2200 Powell St., #925, Emeryville, CA 94608, 510-428-2907, e-mail Mattalla@wje.c*

that were observed to have been permanently displaced as a result of the earthquake. The study found that of the 59 buildings identified with permanent lateral displacements, 58 had experienced a northward or southward component of permanent displacement with no reported eastward or westward component [Paret, et al., 1997]. A number of buildings in that study were welded steel moment frame structures.

From this, it follows that weld fracturing caused by the Northridge earthquake in steel moment frame buildings in the San Fernando Valley ought to have occurred more frequently in frames resisting north-south ground motion than in frames resisting east-west ground motion, and it follows moreover that for any category of reported damage that is related to original construction rather than to the earthquake, the north-south bias hypothesized for earthquake-related damage ought not to exist. Construction related conditions ought to be similarly distributed in both north-south and east-west oriented frames.

To study this hypothesis, all the buildings in the City files that were located in the San Fernando Valley were sifted from the full sample and all the obvious torsionally irregular buildings were discarded because buildings that responded torsionally could muddy the distinction between north-south and east-west orientations of damage. After the sifting, 35 torsionally regular buildings located in the San Fernando Valley were identified. As shown in Table 1, of the 3,449 connections in the north-south frames and 3,985 connections in the east-west frames of these 35 buildings, 1307 or 38% and 1272 or 32%, respectively, were subjected to post-Northridge inspection. The inspection forms for all the inspected connections were reviewed and each connection was classified as containing either a W1 or a non-W1 or as having no reported condition (Table 1). The non-W1 category included all occurrences of weld damage not falling into either W1 or W5, and all occurrences of G-type damage, C-type damage, S-type damage, and P-type damage as defined in the SAC Interim Guidelines [SAC,1995].

Table 1

	North-South Frames	East-West Frames
Total number of connections	3,449	3,985
Number of connections inspected	1,307 (38%)	1,272 (32%)
Number of W1's found	223	262
Number of non-W1's found	171	59

The frequency of occurrence of W1 and non-W1 conditions was computed as a ratio between the number of occurrences of each found, and either the total number of connections in the respective frames in the building or the total number of connections inspected in those frames. The choice of which method to use depends upon whether or not one assumes that the inspection methodology used successfully located all or nearly all occurrences of W1 and non-W1, even in those instances in which the inspection program was terminated prior to each and every connection having been inspected. For this study both possibilities have been explored and are presented in Table 2 and in Figures 1A and 1B, where it can be seen that the reported frequency of occurrence for non-W1 conditions is far higher in the north-south oriented frames than in the east-west oriented frames, while the reported frequency of occurrence for W1's is approximately equal in the two directions, regardless of the method of calculation assumed. Table 2 also summarizes for both W1's and non-W1's the ratios between the reported frequency of occurrence in the north-south oriented and east-west oriented frames (N-S/E-W). The differences between these ratios are so extreme that there does not appear to be any reasonable explanation for this other than the obvious---that non-W1 conditions are related to earthquake motions while W1 conditions are not.

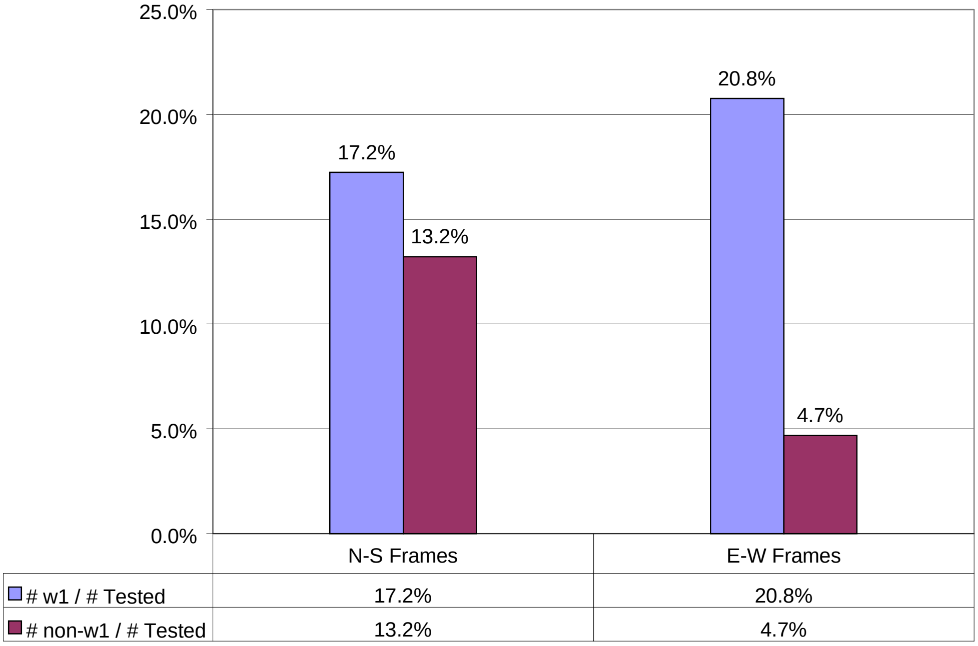

Figure 1A. Frequency of Occurrence of W1 and non-W1 Relative to Total Number of Connections.

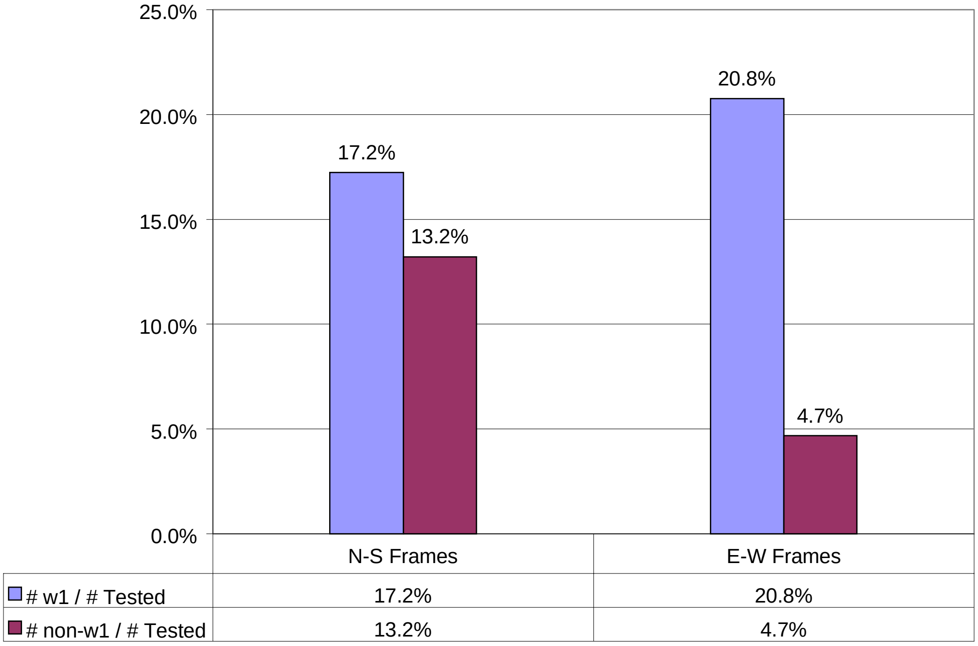

Figure 1B. Frequency of Occurrence of W1 and non-W1 Relative to Number of Inspected Connections.

In recognition of the possibility that the universe of connections against which the frequency of occurrence for W1's ought to be computed should not include those connections already determined to be damaged, i.e. those with non-W1's, the data was reorganized by subtracting the number of non-W1 conditions either from the total number of connections in the sample or from the total number of inspected connections and using that number as the denominator in the calculations (Table 2). The revised computations still clearly communicate the apparent neutrality of W1's with respect to direction and the strong directional bias of non-W1's; thus, underscoring the absence of any relationship between W1's and earthquake ground motion.

Table 2

	Frequency of Occurrence		
	North-South	East-West	(N-S)/(E-W)
#W1/Total # Connections	6.5%	6.6%	.98
#Non-W1/Total # Connections	5.0%	1.5%	3.35
#W1/Total # Inspected Connections	17.2%	20.8%	.83
#Non-W1/Total # Inspected Connections	13.2%	4.7%	2.82
#W1/(Total # Connections - #Non-W1)	6.8%	6.7%	1.02
#Non-W1/Total # Connections	5.0%	1.5%	3.35
#W1/(Total # Inspected Connections-Non-W1)	19.9%	21.8%	.91
#Non-W1/Total # Inspected Connections	13.2%	4.7%	2.82

DISTRIBUTION OF CONDITIONS FOUND IN ALL BUILDINGS IN CITY OF LOS ANGELES FILES

Most tabulations of damaged steel frame buildings since Northridge (e.g., over 100 or over 200 severely damaged buildings, etc.) appear to be based upon the assumption that W1 conditions found during post-earthquake inspection were caused by the Northridge earthquake. However, given the data showing that the occurrence of W1's does not seem to bear any statistical relationship to earthquake ground motions, it is valuable to re-evaluate the largest known inventory of data on earthquake damaged welded moment frame buildings to determine the actual distribution of earthquake related damage---i.e., the distribution of non-W1 conditions---in order to better characterize the extent of weld fracturing caused by the Northridge earthquake. The buildings in this inventory are located in the regions of strongest ground shaking experienced by Los Angeles, as determined by the group that defined the geographic boundaries for the mandatory inspections, and are therefore those buildings most likely to have experienced significant weld fracturing.

Table 3

		% of Tested Connections	% of all Connections
# of buildings reviewed	209	--	--
# of connections	60,981	--	--
# of inspected connections	17,732	100%	29%
# of connections with W1	2,523	14%	4%
# of connections with non-W1	1,341	7.5%	2%

Table 3 summarizes the raw data collected and the frequency of occurrence for W1's and non-W1's. As described earlier, because it is not clear if the SAC inspection methodology actually results in the discovery of all or nearly all occurrences of damage, the frequency of occurrence for W1 and non-W1 conditions are evaluated both with respect to the total number of connections in the buildings and/or with respect to the total number of inspected connections.

In keeping with the previous conclusions, i.e., that only non-W1's signify earthquake damage, and allowing that the SAC inspection methodology did result in most if not all of the non-W1's in each of the buildings inspected after the earthquake being found, it can be seen that only 2% of all the connections in all the buildings in the regions of strongest ground shaking experienced earthquake induced fracturing. It is also noteworthy that with respect to both the total number of connections and to the total number of inspected connections, approximately two-thirds of all reported conditions were W1's. Assuming that most of these W1's were considered to be earthquake damage by the reporting engineers responsible for the post-Northridge earthquake inspection reports, this implies that only about one-third of all reported earthquake damage was actually related to the earthquake.

The entire data set was sorted by building and by category of damage found in each building. These sorts revealed that about one-third of the buildings in the City of Los Angeles sample contained no reported occurrences of either W1 or non-W1; about one-third of the buildings in the sample contained W1 occurrences only with no reported non-W1's; and about one-third of the buildings in the sample contained one or more reported non-W1's. The actual percentage of buildings found in each category is shown in the pie chart in Figure 2. Considering that the buildings in the sample are those that were located in the region of strongest shaking, the fact that two-thirds of the buildings inspected experienced no reported non-W1 occurrences whatsoever is striking. More striking is the statistical breakdown of the subgroup of buildings that were found to have non-W1 occurrences. Figure 2 shows that of the buildings in this subgroup, two-thirds were reported to have fewer than 10% of their connections fractured and only one-third was found to have a non-W1 frequency of occurrence greater than 10%. Therefore, in the region of strongest ground shaking only 24 buildings (11% of the total sample) were found to have more than 10% of their connections damaged by the earthquake. For many engineers, a 10% threshold of damage is considered to be the point at which damage might be characterized as considerable. In accordance with this characterization therefore, the scope of the "welded moment frame problem"---previously characterized as having resulted in many scores of severely damaged buildings---appears to be greatly reduced.

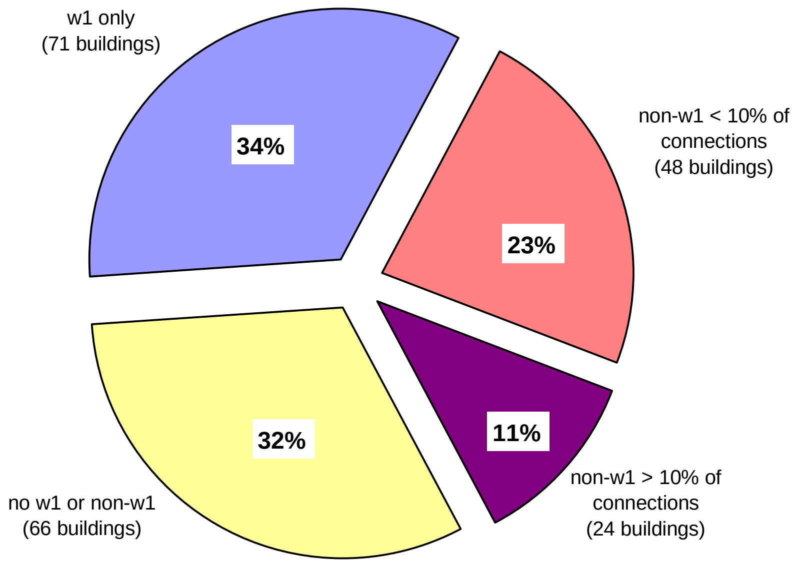

Figure 2. Pie Chart Depicting Distribution of Buildings with W1s and non-W1s

Based upon the above sort, Figure 3 was generated which displays a curve characterizing the cumulative occurrence of non-W1's in the City of Los Angeles inventory of buildings. On the horizontal axis, the building inventory is ranked by increasing number of non-W1's found in each building, and on the vertical axis the cumulative number of non-W1's found in the inventory is recorded. The curve reflects some of the values reported in Figure 2, namely that 137 buildings (66 with no reported W1 or non-W1 occurrences and 71 with only W1, but no non-W1 occurrences) did not experience any reported non-W1 occurrences. The right-most portion of the curve where the slope increases dramatically is especially enlightening. It can be seen for example that relatively few buildings account for most of the non-W1 occurrences in the inventory. In fact, analysis of the data on which this curve is based shows that only seven buildings in the total inventory (i.e., 3% of the total buildings) account for 53% of all the non-W1 occurrences reported in the City of Los Angeles files. In other words, 53% of all the weld fractures reported in all the buildings required to be inspected by the City of Los Angeles ordinance was found in only seven buildings. The data further shows that only 27 of the buildings in the total inventory (i.e., 13% of the total buildings) account for 90% of all the reported non-W1 occurrences. Again, in other words, 90% of all the weld fractures reported in all the buildings required to be inspected by the City of Los Angeles ordinance was found in only 27 buildings. With this data, it can be seen that the true extent of the weld fracturing phenomenon reported after Northridge is not nearly as great as has been previously thought.

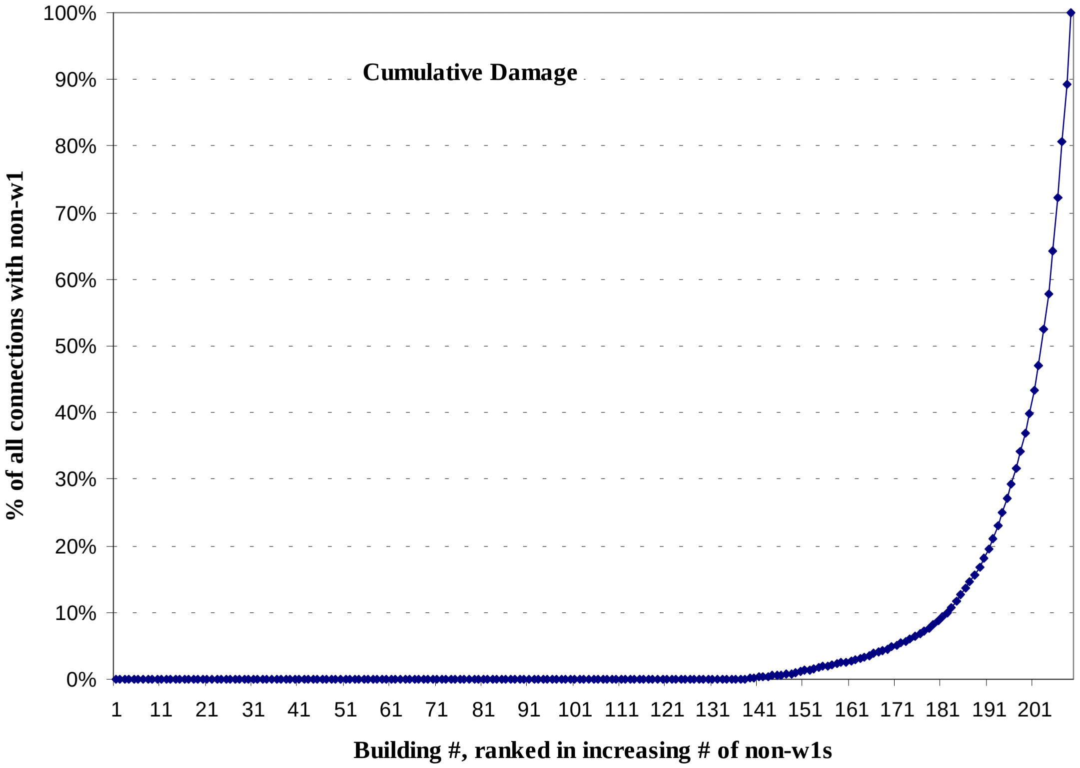

Figure 3. Cumulative Occurrence of non-W1s in City of Los Angeles Inventory

EVALUATION OF THE RELATIVE EFFECTIVENESS OF VISUAL AND ULTRASONIC INSPECTION FOR POST-EARTHQUAKE DAMAGE INVESTIGATION

The data in the City of Los Angeles files provides an unparalleled opportunity to evaluate the post-Northridge earthquake inspection methods used to identify earthquake damage. Per Table 3, 17,732 connections were inspected in the 209 buildings studied, and these 209 buildings contained 60,981 welded moment connections. The fruits of these 17,732 inspections were the identification of 1,341 earthquake damaged joints (non-W1's), which represent just 2% of the total connections in the building or just 7.5% of the total inspected connections. Review of the inspection reports suggests that nearly all these inspections followed SAC-type recommendations and involved exposing significant portions of the beam flanges and web, and column flanges and web, and subsequent ultrasonic inspection and replacement of removed fireproofing. Using a figure of $1,000 to represent the costs associated with each of these inspections, it can be seen that $17,732,000 was expended in the course of identifying the 1,341 damaged joints---an effective unit cost per damaged joint found of $13,223. Although these inspections also located roughly twice that number of W1's, bringing the combined unit cost for finding W1's and non-W1's down to $4,589, this benefit is fictitious for owners interested only in identifying and repairing earthquake damage.

The primary components which drive the costs associated with SAC-type inspections are the requirement for ultrasonic inspection and the fireproofing related expenses. While there is no question that UT is of some benefit when the goal of an inspection is to find W1 type defects within the weld that cannot be observed without ultrasonics, no studies to-date have addressed the necessity of UT for finding non-W1 conditions, and more specifically for identifying buildings with significant numbers of non-W1's. Of primary interest to this study, therefore, was the post-earthquake inspector's characterization of each of the non-W1's found as either visually detectable or not visually detectable---because a visually detectable non-W1 would not have required utilization of ultrasonic methods to find it. Similarly, the locations of the visually detectable non-W1's are equally important. If non-W1's were to be determined to be visually identifiable with regularity and within a relatively small area, tremendous savings might be possible by eliminating the need for large scale removal of fireproofing to expose large areas of the connection for examination and ultrasonic inspection.

Given that the priority of post-earthquake damage inspection is to identify significantly damaged buildings, this study focused on those buildings in the inventory found to have sustained non-W1 damage to more than 10% of their connections. The study was designed to test the hypothesis that these more significantly damaged buildings could have been identified using only a limited visual inspection without the support of ultrasonics and without the removal of large amounts of fireproofing. As described earlier, 24 buildings in the City of Los Angeles inventory were found to have sustained non-W1 damage to more than 10% of their connections. 1,164 occurrences of non-W1's were identified in these 24 buildings, representing 87% of the total number of non-W1 occurrences found in all the buildings in the City of Los Angeles files studied. Of these, sufficient consistency of reporting approach allowed 23 of the buildings to be considered in this study.

In the 23 buildings studied in detail, it was found that 85% of the non-W1 occurrences were noted by the inspectors to have been visually observable, and all of these were visible within a relatively small area, i.e., within 2 to 3 inches of the welded joint. Given the fact that merely noting on the inspection form that a given condition was visually detectable is an extra step for the inspector, it is likely that in at least some of the instances in which a non-W1 was not noted to be visually detectable, this might have been due to an oversight rather than to an absence of any visual surface manifestation of the non-W1. In any case, an 85% success rate in locating damage using only visual inspection is quite palatable especially if the reduced costs of performing visual inspection allow significantly more connections to be inspected.

To verify that each of the buildings in this group of 23 buildings could have been individually identified as damaged using only visual inspection, each building was individually evaluated for visual detectability of its non-W1's. In all but two of the buildings in the group at least 70% of the non-W1's were visually detectable. While the inspection reports indicate that in two of the buildings approximately 40% and 50% of the non-W1's were visually detectable, we suspect that these relatively low rates are an artifact of either the particular inspectors on those projects or of the inspection form rather than an accurate characterization of the observability of the non-W1's in those buildings. In any case, even when visual inspection can only successfully locate 40% of the non-W1 conditions in a building, visual inspection is still a far more cost-effective tool than ultrasonic inspection for identifying buildings with significant numbers of fractures because visual inspection of a connection costs only about $100 vs. $1,000 for a SAC-style ultrasonic inspection. Using a SAC-type methodology in which a first pass inspection consists of UT and involves roughly 15% of the connections in a building, for a building with 1,000 connections, 150 connections can be inspected at a cost of about $150,000. Assuming in this case that non-W1's were uniformly distributed throughout the building, at most 15% of the damage in the building could have been found. Using visual inspection, however, 50% of the connections in the building could have been inspected for $50,000, which is only one-third of the cost of the UT inspection. With the same uniform distribution of non-W1's previously assumed, and in the worst case assuming that only 40% of the non-W1's could be detected, it can be seen 20% of the non-W1's in the building would have been found by visual inspection compared to only 15% for the UT inspection. In the more typical case, however, assuming 80% of the non-W1's are visually detectable, 40% of the non-W1's in the building would have been found. In this context, reliance on UT for post-earthquake identification of significantly damaged buildings can be seen to be inappropriate. Visual inspection provides a better indication of the extent of the damage in a building for significantly less cost.

REFERENCES

Paret, Terrence F., M. R. Attalla, S.A. Freeman, and G. Borchardt, 1997, "Permanent Directed Deformations of Buildings as Evidence for a Directed Near-Field Impulse in the M6.7 Northridge Earthquake of January 17, 1994", The Northridge Earthquake Research Conference, August 20-22, 1997, Los Angeles, California, sponsored by California Universities for Research in Earthquake Engineering (CUREe), Richmond, CA.

Paret, Terrence F. and S.A. Freeman, 1997, "Is Steel Frame Damage Being Diagnosed Correctly?", Building to Last, Proceedings of Structures Congress XV, Structural Engineering Institute/ASCE, April 13-16, 1997, Portland, Oregon.

SAC Joint Venture, 1995, Interim Guidelines: Evaluation, Repair, Modification and Design of Welded Steel Moment Frame Structures, FEMA 267, Report No. SAC-95-02, August 1995.

ACKNOWLEDGEMENTS AND DISCLOSURES

A portion of the work forming the basis for this publication was conducted pursuant to a contract with the Federal Emergency Management Agency whose assistance is gratefully acknowledged. The substance of such work is dedicated to the public. The authors also wish to acknowledge the assistance of the City of Los Angeles Department of Building and Safety for compiling and providing access to the WSMF inspection reports.

The authors are solely responsible for the accuracy of statements or interpretations contained in this publication. No warranty is offered with regard to the results, findings, and recommendations contained herein, either by Wiss, Janney, Elstner Associates, Inc., the Federal Emergency Management Agency, the SAC Joint Venture, the individual joint venture partners, their directors, members, or employees. These organizations and individuals do not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any of the information, product, or processes included in this publication.