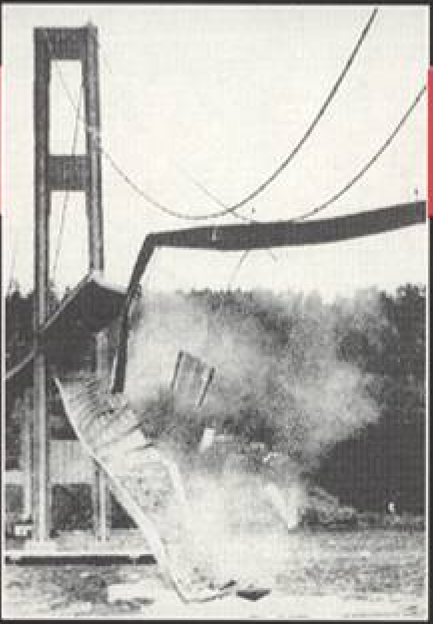
AUG. 1996 VOL. 10 NO. 3
ISSN 0887-3828
CODEN: JPCFEV

JOURNAL OF PERFORMANCE OF CONSTRUCTED FACILITIES



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QUALITY CONTROL IN SEISMIC DESIGN AND CONSTRUCTION

By G. G. Schierle[1]

ABSTRACT: This paper presents research on quality control in seismic-resistant construction. The research objective was to verify compliance with seismic safety features in light residential and commercial wood construction. While the study was on quality control in seismic-resistant construction, the results apply to wind conditions and design flaws as well. The study included two methods: (1) mail surveys of architects and engineers; and (2) site surveys of projects under construction. Results are presented in graphs for visual comparison. Both surveys revealed that more than one-third of seismic safety items were missing or flawed in over 40% of surveyed units (apartments, etc.). It is alarming that the key items to resist wind and seismic loads are among those most frequently missing or flawed, including shear wall hold-downs, nailing, and proportion (aspect ratio); wall-to-wall straps and tie-downs, diaphragm blocking and nailing, drag strut splice, and roof-to-wall anchors. Conclusions include recommendations to improve quality control.

INTRODUCTION

The knowledge base for seismic design has greatly advanced in recent decades as a result of observations and research on building response to earthquakes and progress in computer-aided engineering. However, implementation of research results in design and construction practice does not automatically follow. Yet, earthquake safety of actual buildings is the ultimate goal of all research in this area. There is clearly a need for research to determine the level and quality of seismic design implementation in actual construction. Construction quality control in general is an important issue. It greatly affects, for better or worse, public safety and public perception of the building community, including architects, engineers, building officials, contractors, developers, and owners. The issue is magnified when safety during earthquake or wind disasters is concerned. The dramatic nature of such events impacts public confidence in the quality of the built environment. The devastating hurricane Andrew of 1992 and the Northridge earthquake of 1994 demonstrated this point. Media accounts of those events and construction failures resulting from them had a chilling effect on public confidence in the building community. This affects all involved in the process, not just those responsible for poor construction practices.

Frohnsdorff, speaking as chief of the building Material Division of the National Bureau of Standards (NBS) [now National Institute of Standards and Technology (NIST)] at a Dallas conference on quality assurance in the building community, estimated the cost of construction defects at 9.5 billion dollars in 1982. The writer, inspecting one of his projects during construction in 1985, found 10 of 34 hold-downs, shown on the plans, missing. It took repeated requests to get them installed. The Bay Area Earthquake Preparedness Project (*Network* 1987) reported that on the 1987 Whittier Narrows earthquake 120 wood-frame homes were destroyed due to foundation failures. Another 500 suffered severe damage, while more than 2,600 experienced minor damage. The report also stated, ''Current practices, building code requirements for foundation design, seismic bracing, and bolting of structures to foundations should have eliminated this type of damage in buildings. . . . There were notable examples of damage to newer wood frame buildings where seismic bracing was not adequate.'' It is obvious that much of the damage was avoidable. Earthquakes also cause damage to nonstructural items with repair costs often higher than structural repair. Lagorio (1990) reported that nonstructural damage can amount to as much as 70% of future repair or replacement costs. The Northridge earthquake of January 17, 1994 caused property damage estimated to exceed 15 billion dollars. The city of Los Angeles alone recorded more than 100,000 damaged structures. The *Los Angeles Times* reported, on its April 21, 1994 cover, at least one-third of the earthquake damage could be attributed to flawed construction. Inadequate quality control indeed results in very high costs to society. The foregoing observations prompted the study on quality control in light residential and commercial wood construction that is less observed by design professionals than other types.

QUALITY CONTROL STUDY

The study on quality control conducted by the writer (Schierle 1993) included two methods: (1) mail surveys of architects and engineers; and (2) site surveys of projects under construction, respectively referred to as mail survey and site survey. The two methods provided a means to compare the findings. The mail surveys asked architects and engineers to report experiences with quality control for earthquake safety on a questionnaire similar to a checklist prepared for the site surveys. For the site surveys, research teams surveyed projects under construction, prior to sheathing, for an open view of items. The results of these surveys are presented in Figs. 1–3.

Mail Survey

A survey questionnaire was mailed to over 3,000 architects and engineers licensed in California. They were selected at random from mailing lists provided by the California chapter of the American Institute of Architects and the Structural Engineers Association of Southern California. The surveys were mailed in June 1992 with prestamped return envelopes. Most replies were returned during the following two months. Of the 150 responses, 135 were usable. Fifteen could not be used in the statistical graphs, because they did not provide numerical answers. Some responses included multiple projects, but most were for single projects. A majority came from southern California, some were from northern California, and a few were from other states. The mail survey included 28 items for seismic resistance with option for items to be added by respondents under each category. It was assumed that if enough similar items would be added, they could be included with the final results. However, the responses did not include a sufficient number of added items to justify their inclusion in the results. Several respondents included written comments on the questionnaire or in letters.

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Note. Discussion open until January 1, 1997. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on April 24, 1995. This paper is part of the ***Journal of Performance of Constructed Facilities***, Vol. 10, No. 3, August, 1996. ©ASCE, ISSN 0887-3828/96/0003-0090–0095/$4.00 + $.50 per page. Paper No. 10578.

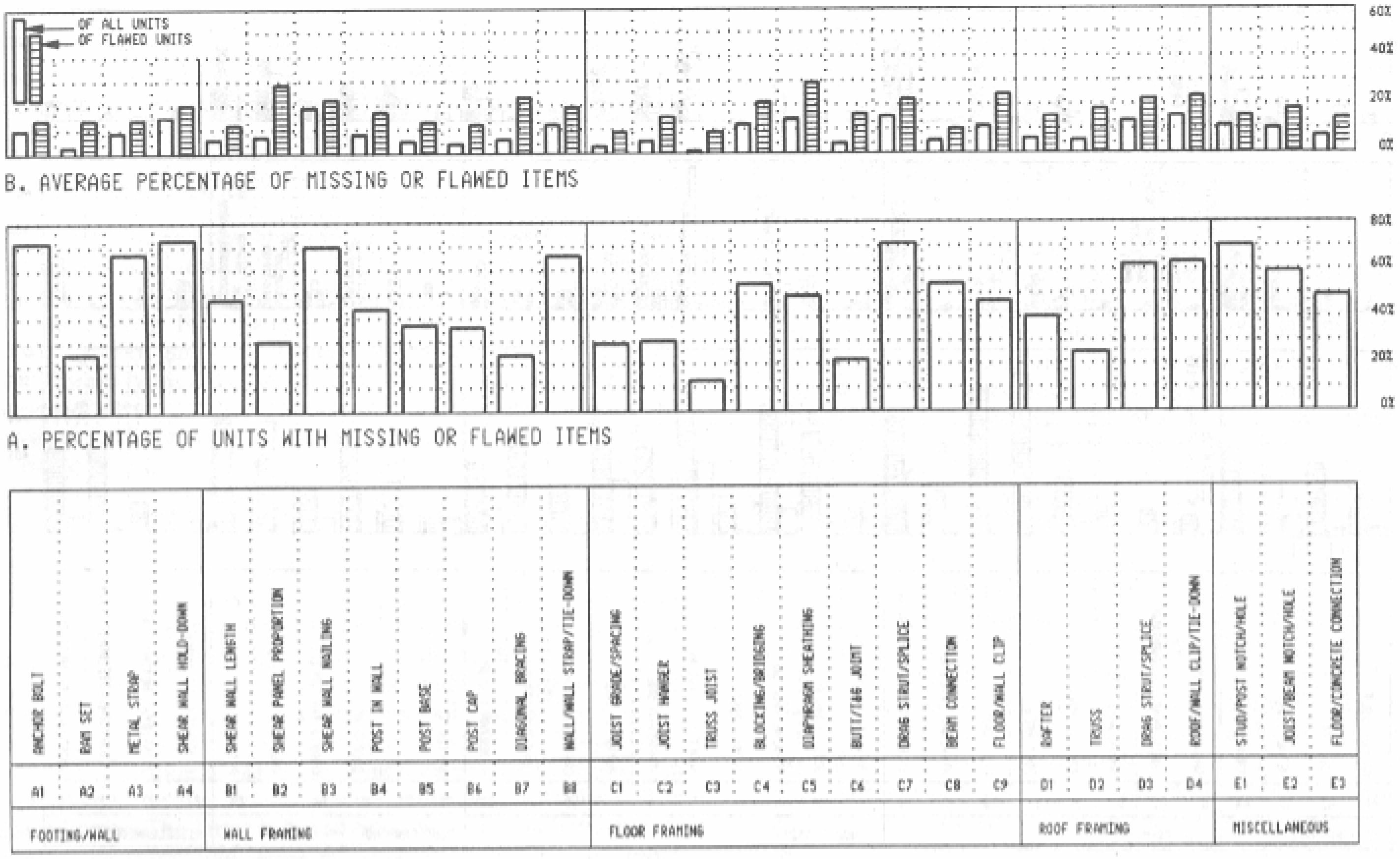

FIG. 1. Mail Survey

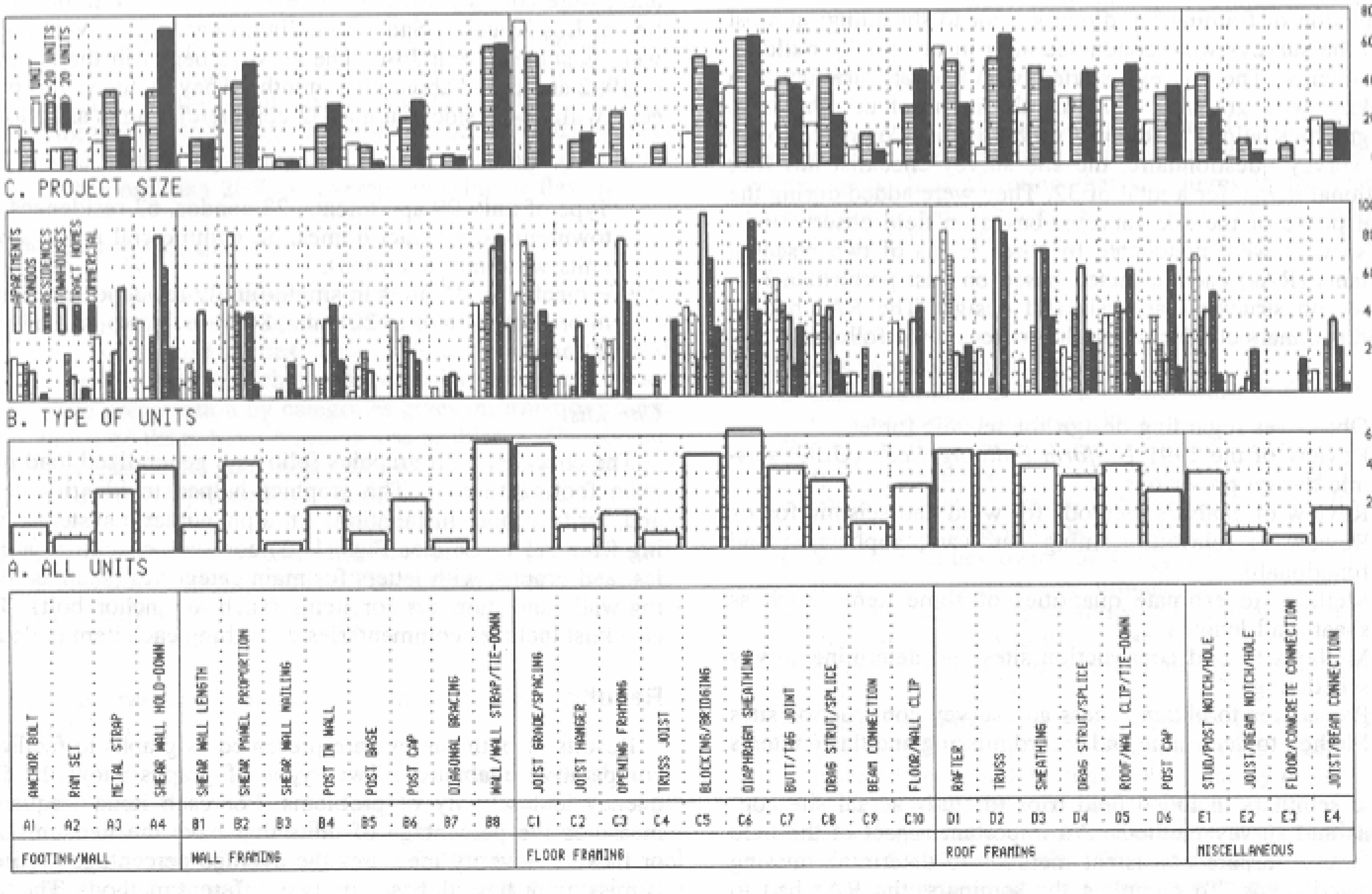

FIG. 2. Percentage of Site Survey Units with Missing or Flawed Items

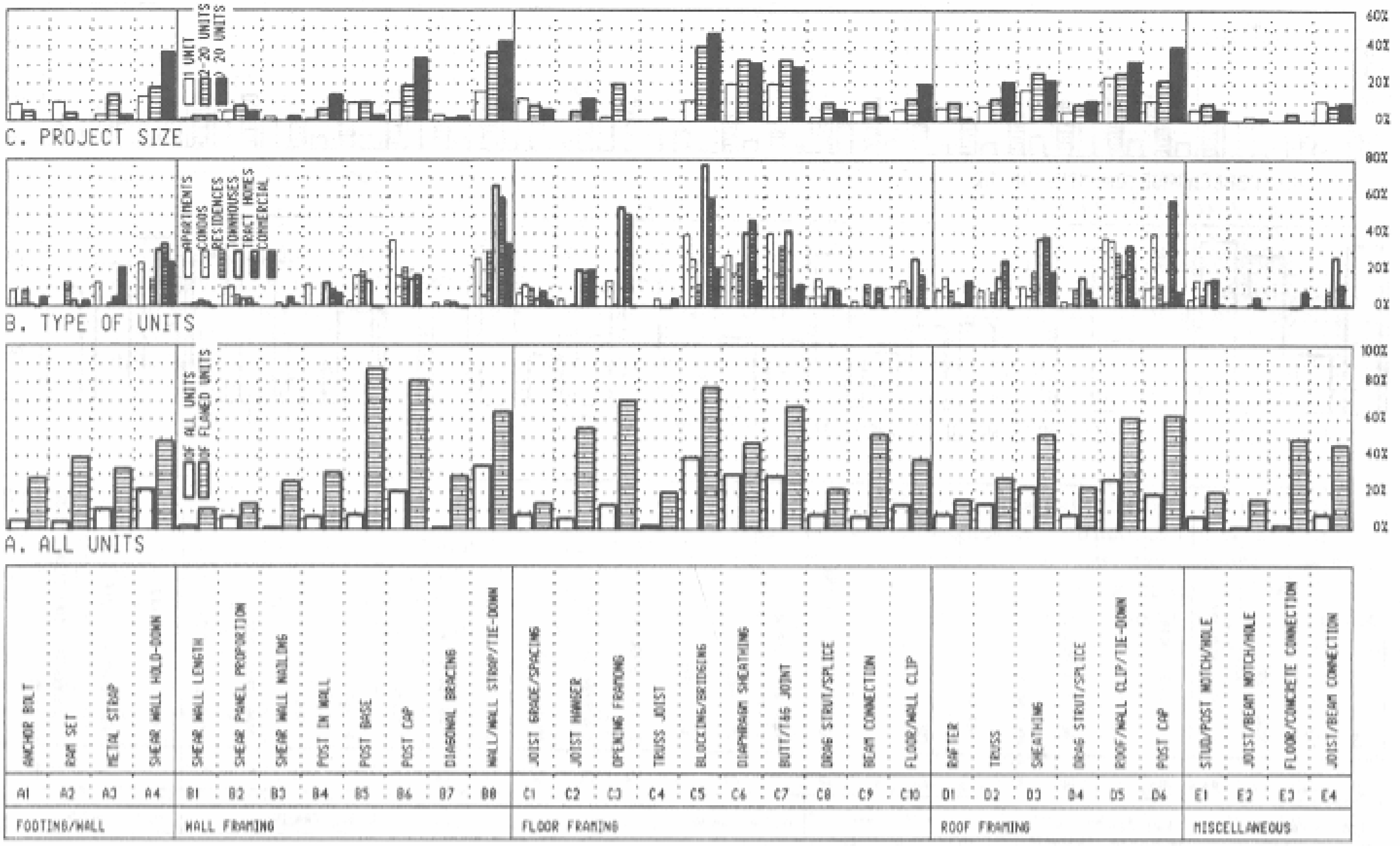

FIG. 3. Average Percentage of Missing or Flawed Items in Site Survey Units

Site Survey

To assure an unobstructed view of surveyed items, the site surveys were conducted on projects under construction, after completion of framing but directly prior to sheathing; in most cases the surveys were conducted after inspection by building departments. The surveys started with the preparation of a checklist with graphics depicting the items of the checklist. The graphics helped to identify survey items. Compared to the mail survey questionnaire, the site survey checklist has four additional items, for a total of 32. They were added during the initial phase of the site surveys, based on field observations. The surveys were conducted by three teams of two research assistants (RAs) each, selected based on past performance in courses on structural analysis and design. The RAs had to attend seminars conducted by the writer on the following topics:

- Objectives regarding design for seismic forces
- Review of the 1991 *Uniform Building Code* (UBC) seismic design provisions
- Review of analysis methods for wind and seismic forces
- Review of relevant framing hardware, application and functionality
- Methods to estimate quantities of some items, such as shear-wall lengths
- Methods to find construction sites and determine survey scheduling
- Procedures to obtain access and survey construction sites
- Method to determine and record missing and flawed items

The seminars included field trips to study actual site conditions and survey methods. An important aspect of the field trips was to assure consistent methods to determine missing or flawed items. To complete the seminars, the RAs had to pass a written examination that included situations they might encounter in the field. After passing the examination, they started conducting the site surveys. Weekly seminars during the surveys helped to coordinate and refine the survey method and assure consistency. The surveyed projects are in the counties of Los Angeles, San Bernardino, Orange, and Ventura, as well as some in San Jose. The surveys began in the summer of 1992 and lasted about nine months. They included 143 projects, with 264 residential and 32 commercial units as follows:

- Type of unit: 99 apartments, 23 condos, 63 residences, 28 townhouses, 42 tract homes, 32 commercial units (seven units were not identified).
- Project size: 45 units in single-family residences, 60 units in projects of two to 20 units, 86 units in projects of over 20 units.

Checklist

The checklist with graphics follows a generalized load path from footing to roof. The graphics helped to identify items and verify proper installation. An alphanumeric system ranging from A1 to E4 (see Figs. 1–3) correlate checklist, graphics, and graphs, with letters for main categories (such as footing/wall) and numbers for items (such as anchor bolt). The checklist includes commentaries describing each item in detail.

Results

Results of both surveys are presented as graphs to facilitate comparative evaluation. Two types of graphs show the frequency and severity of problems. For each item, frequency measures the percentage of units that have the item missing or flawed. Severity measures the average percentage the item is missing or flawed, based on two different methods. The first method has percentages based on all surveyed units. The second method has percentages based on only those units that have any of the respective items missing or flawed. The first method gives an indication of how severe the problem is overall, while the second method looks only at problem units and ignores all others in the percentage count.

Mail Survey Results

The mail survey responses from architects and engineers did not have consistent information for statistically meaningful breakdowns by type of units or project size, as was done for the site survey. For example, several respondents did not indicate type of units, or reported averages of several projects of different types. The project size was also missing on several returned surveys. Therefore, presentation of the mail survey findings is limited to one graph showing frequency and severity of missing or flawed items in A and B, respectively.

Fig. 1: Mail Survey

This graph includes in A and B, respectively, the ''percentage of units with missing or flawed items'' and ''average percentage of missing or flawed items'' illustrating the frequency and severity of problems. Graph A shows the frequency of problems as a percentage of units with missing or flawed items. For example, Item A1, anchor bolt, shows 72% of the units have missing or flawed anchor bolts. Graph B shows the severity of problems as an average percentage of missing or flawed items in two ways: as a percentage of all units and of flawed units. The latter is based only on units that have at least one of the respective items missing or flawed. For example, item A4, shear-wall hold-down, shows overall 15% hold-downs missing or flawed, but 20% when units with no missing or flawed hold-downs are excluded.

Some observations are of interest. The frequency of units with missing or flawed items ranges from a minimum of 13% to a maximum of 72%. Of the 28 items surveyed, 17 items are missing or flawed in over 40% of recorded units. Key items to resist seismic loads are among those that are most frequently missing or flawed, including shear-wall hold-downs and nailing; wall-to-wall straps and tie-downs; diaphragm blocking and nailing; drag strut splices; roof-to-wall clips; and tie-downs. These key items also have the highest severity rating, with more than 20% on average missing or flawed.

Site Survey Results

Close supervision allowed the site surveys to be conducted with tighter control and consistency than the mail survey that had to rely on third parties. This made it possible to provide graphs by categories, such as type of units (apartment, condo, etc.). The presentation by categories gives information regarding which of these have more or less problems. The site surveys are based on 264 residential and 32 commercial units surveyed in 143 projects. A condo is defined as a unit with party walls and floors, while a townhouse is defined as a unit with party walls but no party floors. A residence is defined as a single-family detached house. The number of units surveyed on each project ranged from one to three, and on very large projects, to more than three.

Fig. 2: Percentage of Site Survey Units with Missing or Flawed Items

This graph gives the frequency of missing or flawed items. For each item, it shows the percentage of units that have some of those items missing or flawed. The data is presented in graphs A, B, and C for ''all units,'' ''type of units,'' and ''project size,'' respectively. For Example, Item A4, shear-wall hold-down, shows 45% of recorded units have missing or flawed hold-downs. Graph A has missing or flawed items for all units. Graph B itemizes unit types by apartments, condos, etc. Graph C itemizes projects of one unit, two to 20 units, and over 20 units.

Fig. 3: Average Percentage of Missing or Flawed Items in Site Survey Units

This graph gives the severity of missing or flawed items. For each item, it shows average percentages by which the respective item is missing or flawed. The data are presented in graphs A, B, and C for ''all units,'' ''type of units,'' and ''project size,'' respectively. Graph A has percentages based on all units and flawed units. For example, item A4, shear-wall hold-down, shows that 22% of surveyed hold-downs are missing or flawed. However, 48% of hold-downs are missing or flawed when the percentages exclude units without any missing or flawed hold-downs. Graphs B and C have percentages based on all recorded units. Graph B is itemized for apartments, condos, etc. Graph C is itemized by project size for one unit, two to 20 units, and over 20 units.

Again, some observations are of interest. The percentage of units with missing or flawed items ranges from a minimum of 4% to a maximum of 58%. Of the 32 items surveyed, 11 are missing or flawed in more than 40% of recorded units. As in the mail survey, key items to resist seismic loads are among those missing or flawed in over 40% of recorded units. They include shear-wall hold-downs, shear-wall proportion, wall-to-wall strap or tie-down, diaphragm blocking and nailing, roof sheathing, and roof-to-wall anchors. About 35% units have missing or flawed metal straps and drag strut splices. Compared to the mail survey, shear-wall nailing shows fewer problems because RAs did not know what nail type or spacing was specified and checked only for the UBC maximum spacing allowed. Single-family residences have the least problems, while town houses and tract homes have the most. Further, large projects have more problems than small ones.

Comment on Results

Both the mail and site surveys revealed over one-third of the items surveyed missing or flawed in at least 40% of recorded units. It is alarming that key items in the load path from roof to foundation are among those most frequently missing or flawed. Referring to Fig. 4, those missing or flawed key items include

A Shear-wall anchor bolt—to attach walls to the foundation to resist lateral slippage.
B Shear-wall hold-down—to anchor walls to foundations to resist overturning under load.
C Shear-wall nailing—to secure plywood panel edges nail spacing should be 6 in. (15 cm) or less per UBS (1991), yet many panels have nails spaced up to 16 in. (40 cm), or nails that miss framing members.
D Wall-to-wall tie-down—to tie upper floor shear walls to those below to resist overturning.
E Framing anchor—to tie roofs and floors to shear walls and walls to walls to transfer shear.
F Beam connection—to secure beams from sliding off a wall or other support.
G Shear-wall proportion—according to UBC table 25-I (1991) this should not be less than 1:3.5. The survey revealed walls of 1:18. This point, a likely design flaw, is discussed in the following section.
H Blocking—of floor joists to nail adjacent plywood panel edges for shear transfer. Without it, diaphragms have only about one-half the shear capacity per UBC table 25-J-1.

Design Flaws

The site surveys, while focused on construction quality, revealed design flaws as well. Some were obvious design flaws while others may be design or construction flaws. Example of design flaws include: narrow shear walls with extreme width/height ratios; soft-story parking under apartments; and problem configurations.

Narrow Shear Walls

According to UBC (1991) table 25-I maximum plywood shear wall width/height ratios should be 1:3.5 (a May 20, 1994 emergency enforcement measure of the Los Angeles Department of Building and Safety limits the ratio to 1:2). However, many shear walls surveyed exceeded the 1:3.5 limit substantially. The shear wall in Fig. 5 is 30 in. (75 cm) wide, extending five stories high for a ratio of 1:18 without being connected to moment-resistant beams at intermediate floors. Such walls are vulnerable to overturning and buckling under lateral load and clearly should be avoided. An architectural alternative to narrow walls would be to combine windows in adjacent rooms and to combine two shear walls into a wider one. This could be considered at an early design stage by preliminary computer analysis (Schierle 1992, 1994). An engineering solution would be to anchor the shear walls at each level to edge beams (rim joist), designed to resist overturning in bending.

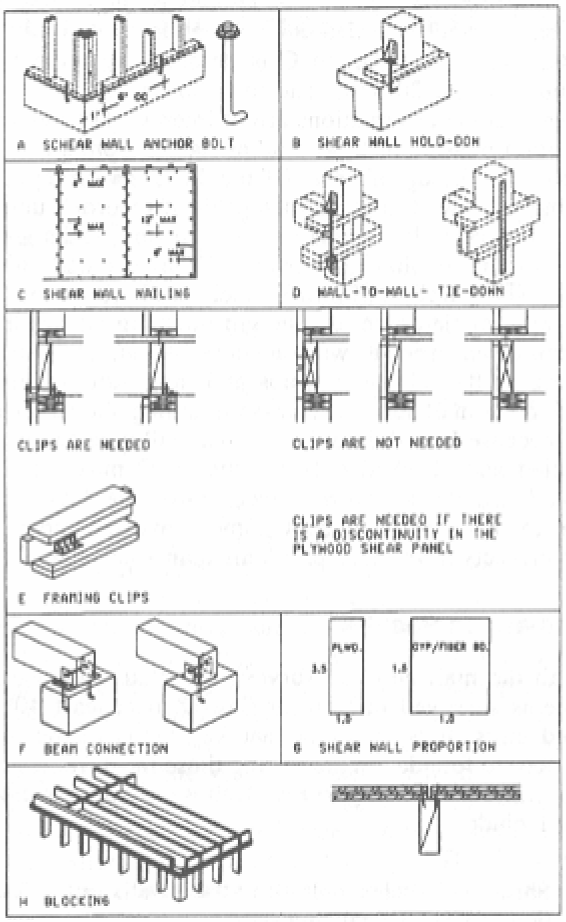

FIG. 4. Missing or Flawed Seismic Safety Items

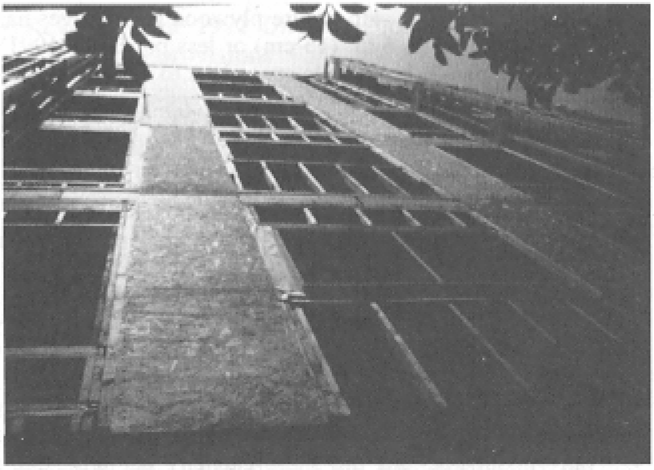

FIG. 5. Extremely Slender Shear Wall

Soft-Story Parking

Soft-story parking under apartment buildings is often supported on columns that are pin-connected at the top and bottom, evidently under the assumption that lateral load would be transferred by floor diaphragms to side and rear walls in torsional shear. However, the frequent lack of blocking in floor diaphragms make them ineffective to transfer shear. The collapse of a soft-story parking in the Northridge earthquake (Fig. 6) is convincing evidence to seek better design practices. The supporting columns should be designed with moment-resistant connections to a grade beam and/or overhead beam of sufficient strength to resist lateral forces and sufficient stiffness to minimize $P\Delta$ moments.

Problem Configurations

Problem configurations of L-, T-, or U-shaped plans are common in apartment buildings. They are vulnerable to failure during earthquakes due to different stiffnesses (Arnold and Reitherman 1982). Vibration of a wing attached to an adjacent

FIG. 6. Collapsed Soft-Story Parking

FIG. 7. Failed Roof Diaphragm at L-Shaped Intersection

wing of different periods may cause torsion (Fig. 7). To prevent failure, wings should be either separated by seismic joints or strengthened at their intersections.

CONCLUSIONS

The foregoing results are compelling evidence that quality control for seismic design and construction should be improved. Even though the loss of life in the Northridge earthquake was modest compared to similar quakes elsewhere, the heavy economic losses could have been much less, given better quality control. The cost to correct flawed construction is usually much higher than if the building were built correctly from the start. This is due to several factors: removing and redoing finishes to gain access to flawed structures; temporary housing in hotels during repair work; and legal costs for litigation or arbitration. These costs, usually paid by insurance carriers, are ultimately paid by society through higher premiums. In the case of natural disasters like earthquakes or wind storms, the costs for repair or replacement are often covered by government agencies. There will always be damage caused by natural disasters, but improved construction quality can greatly reduce this. Much of the widespread destruction caused by the 1994 Northridge earthquake was preventable. A minor investment in better quality would have saved large sums for replacement or repair (Mann 1984). To reduce potential future losses of existing buildings, efforts should also be directed to improve their seismic resistance (Lagorio et al. 1986; Wong 1990).

Future research should test alternatives for items such as diaphragm blocking that are labor-intensive and thus often ignored. For example, the UBC (1991) identifies six schemes of blocking spaced at 4 ft (1.2 m). Blocking at 8 ft (2.4 m) would cost half as much at similar capacity. Hopefully, the findings of this study will help initiate better quality control to mitigate earthquake hazards, reduce costs of future replacement or repair, and, most importantly, save human lives. The building community, from design professional to construction crew, would benefit from better quality control by improved public confidence in the built environment. The building community must act in a positive and constructive manner in addressing this important issue. To ignore quality control and blame future losses as an ''act of God,'' despite the fact that we have the means to mitigate them, is irresponsible.

The following recommendations should improve quality control for earthquake safety:

- The building community should foster cooperation versus confrontation; partnering arrangements have proven to be effective means for quality control (Stephenson 1996).
- Legal disputes should not be allowed to include anyone without reasonable cause, to reduce anxiety and improve cooperation in the building community.
- Architecture schools should improve seismic-design education.
- Trade schools should teach basic rules on seismic-resistant construction.
- Contractor's license tests should include lateral-force-resistance topics.
- Developers should pay design professionals for construction observation.
- Building codes should require construction observation by architects or engineers.
- Building codes should make seismic design objectives more transparent.
- Building inspectors should focus more on items that are often missing or flawed.
- The insurance industry should offer incentives (lower premiums) for good quality control.

ACKNOWLEDGMENTS

This research was funded by the National Science Foundation Grant No. BCS-9203339. Any opinions, findings, conclusions, or recommendations expressed are those of the writer and do not necessarily reflect the views of the National Science Foundation. The writer would like to express his gratitude to Henry Lagorio, former program director of the Earthquake Mitigation Program of the National Science Foundation; to Dimitry Vergun, structural engineer (SE), project consultant; and to the following members of the advisory council for the research: David Chang, SE; Andrea Cohen-Gehring, American Institute of Architects (AIA); Michael Gehring, AIA; Manual Gonzales, AIA; David Green; William Haglund, SE; Peter Knowlton, SE; Ara Maloyan, PE; Thomas Menalo; Rodney Spears, SE; Edward Takahashi, AIA; and Nabih Youssef, SE.

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