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Observation of structural pounding damage from 1989 Loma Prieta earthquake

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ABSTRACT

The survey results on pounding incidents during 1989 Loma Prieta earthquake are summarized. They include the distribution of pounding damage in the specific areas, types of pounding damage, and examples for pounding damage involving major multi-story buildings.

INTRODUCTION

Pounding Incidents. - Structural pounding refers to the lateral collisions of adjacent buildings during earthquakes. Pounding occurs when building separations are insufficient to accommodate the relative motions of adjacent buildings. Pounding damage has been reported from most major earthquakes affecting metropolitan areas of the world. Pounding of adjacent buildings has made damage worse, and/or caused total collapse of the buildings. The earthquake that struck Mexico City in 1985 has revealed the fact that pounding was present in over 40% of 330 collapsed or severely damaged buildings surveyed, and in 15% of all cases it led to collapse (Rosenblueth and Meli 1986). This earthquake illustrated the significant seismic hazard of pounding by having the largest number of buildings damaged by its effect during a single earthquake (Bertero 1986).

Loma Prieta Survey. - The writers have surveyed the damage due to pounding in the San Francisco Bay area during the recent 1989 Loma Prieta Earthquake. The earthquake caused pounding between buildings over a wide geographical area including the cities of San Francisco (e.g., Fig. 1), Oakland (Fig. 2), Santa Cruz, and Watsonville. Significant pounding was observed at sites over 90 km from the epicenter thus indicating the possible catastrophic damage that may occur during future earthquakes having closer epicenters. This paper summarizes the writers' survey results on pounding (Kasai and Maison 1991).

GENERAL SURVEY FINDINGS

Survey Methodology. - This survey is compiled from data provided by: engineers, government officials and engineers, building owners, and block-by-block inspections performed by the writers. The database contains the input of about 90 interested parties and records more than 200 pounding occurrences involving more than 500 structures.

Classification of Pounding Damage. - Pounding damage patterns are classified as follows: Type-1, major structural damage; Type-2, failure and falling of building appurtenances creating a life-safety hazard; Type-3, loss of building function due to failure of key mechanical, electrical or fire protection systems; and Type-4, architectural and/or minor structural damage.

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Survey Findings and Comments. - The following are some of the general survey findings and comments:

(1) The majority of reported cases are in urban areas including San Francisco (e.g., Fig.1), Oakland (Fig. 2), Santa Cruz and Watsonville.
(2) Pounding typically involved multi-story buildings constructed prior to about 1930. They are typically of masonry construction with or without steel skeletal vertical load resisting systems. Very little consideration was given for separation between such buildings to preclude pounding. In many cases, they are in contact with each other.
(3) Fewer modern buildings suffered pounding. In such buildings, relatively larger separations exist. However, it is noted that many modern buildings having expansion joints suffered pounding due to small separations.
(4) There is evidence of correlation between occurrences of pounding and soft foundation soil conditions. This may be attributed to the more intense shaking typically reported for such soil conditions and/or from the possible settlement and rocking of the structures located on soft soils.
(5) Special pounding cases were also observed. They include; severe pounding at unsupported part (e.g., midheight) of columns or walls; pounding promoted by torsional behavior of building; and pounding between the buildings sharing a common wall.
(6) Older buildings that suffered Type-1 damage typically also had Type-2 damage (i.e., falling bricks). Modern buildings that pounded usually had Type-4 damage, and several of them also suffered Type-3 damage. The survey has relative distributions for damage Types 1 and 4 of 21% and 79%, respectively. Many of the present Type-4 damage cases will become damage Types 1, 2, and/or 3 when a future more severe earthquake affects the region. The Type-4 damage cases may be thought of as precursors for the major pounding damage yet to occur.

DISTRIBUTION OF POUNDING DAMAGE IN SELECTED AREAS

The following summarizes the occurrences of pounding for several specific areas. Discussion includes the distribution of pounding damage, earthquake intensity, maximum ground acceleration, soil condition, building density, and building type as well as height.

San Francisco Financial District and South-of-Market Area. - The writers conducted a block-by-block survey of this area. Fig. 1 shows the concentrated study area as specified by the dashed lines, and incidences of pounding are indicated by solid dots. Multi-story office buildings are the typical structures in this area. Heights typically range from 2 to over 20 stories. The area has a mix of older masonry buildings and modern high-rise buildings of concrete and steel construction.

The area experienced significant earthquake motions as indicated by the Modified Mercalli intensity of seven (MM VII) assigned by the United States Geological Survey (USGS). In the north-east corner of the area on a fill area, a peak horizontal ground acceleration of 0.2g was recorded by the California Strong Motion Instrumentation Program (CSMIP). In the region near the east corner of the study area, 0.09g was recorded, on Franciscan sandstone and shale. At about the center of the study area, 0.17g was recorded, on fill over bay mud.

North of Market street, pounding damage is concentrated near the eastern edge of the area associated with loose soil fill where liquefaction was reported. This area was filled in the late 19th century and recorded large ground deformations and soil liquefaction in the 1906 San Francisco earthquake. South of Market, pounding damage is widespread and somewhat concentrated at: (1) south of Mission street between 4th and 7th Streets including the area that was filled in the late 19th century which recorded large ground deformations and soil liquefaction during the 1906 San Francisco earthquake; and, (2) south of Market between 1st and 3rd Streets, which is near the same shore line.

Oakland City Center: The writers also conducted a block-by-block survey of this area. The survey area is shown by the dashed line in Fig. 2, and occurrences of pounding are shown by solid dots. The area has a variety of building sizes that range from small low-rise buildings to large multi-story buildings. In general, the sizes and heights of the buildings are smaller than those in the San Francisco Financial District. The heights typically range from 1 to over 10 stories. The area contains a mix of wooden, older masonry, and modern high-rise buildings of concrete and steel construction.

The area experienced significant earthquake motions as indicated by the Modified Mercalli intensity of eight (MM VIII). At about the center of the concentrated survey area, a peak horizontal ground acceleration of 0.26g was recorded, on alluvium. The entire survey area rests on alluvium soil.

This survey area, which is smaller and having less building density than the San Francisco Financial District, still showed a high occurrence of pounding damage probably because of high ground accelerations in this area. Fig. 2 shows that the pounding damage is concentrated in a densely built area on Broadway and San Pablo Avenues. Significant pounding was present in older masonry as well as wooden buildings.

Other Areas. - The writers also performed a block-by-block review of other areas. The areas are: (1) San Francisco Marina District (MM IX), where 3 and 4 story residential buildings of wood construction are most common (e.g., Fig. 3); (2) The Pacific Garden Mall area (MM VIII) in downtown of Santa Cruz, where most buildings were constructed around the turn of the century. The heights range from 1 to 7 stories but most are typically up to 3 stories. Most of the severely damaged structures are of unreinforced masonry; (3) Watsonville downtown area (MM VIII), where the building heights are typically 2 to 3 stories. Most of these buildings were of masonry construction.

Pounding was present in many buildings in these areas (Kasai and Maison 1991). Further investigation is being conducted by the writers.

EXAMPLE CASES

This section presents actual examples of pounding involving major multi-story buildings. The buildings selected offer information on a variety of pounding mechanisms and consequences. The purpose is to illustrate the various types of major pounding damage caused by the Loma Prieta earthquake in order to clearly inform the engineering community of the significant seismic hazard that pounding poses.

Mission Street, South-of-Market, San Francisco: The building is 10 stories and constructed of masonry combined with a steel skeleton (Fig. 4). It was built in 1904. This building experienced pounding with an adjacent massive 5 story building which occupies most of the city block (Fig. 4(a)). Pounding was located at the 7th level in the 10 story building and at the roof level in the 5 story building. About 1 to 1.5 inch building separation is present. The 10 story building suffered structural damage above the pounding elevation as evidenced by the large diagonal shear cracks in the masonry piers (Fig. 4(b)). This case is classified as Type-1 damage.

Broadway Street, Oakland City Center: The 12 story building consists of an 11 story reinforced concrete structure constructed in 1924 with a penthouse steel structure added in the 1950's (Fig. 5(a)). The adjacent building is a modern 6 story reinforced concrete parking garage. A bridge spans from the parking garage top level to the building at the 8th floor level. The bridge has a sliding connection at the building that provides for about 4 inches of relative building movement. Severe pounding occurred resulting in extensive cracking of the building at the bridge location (Fig. 5(b)). Large interior diagonal shear cracks in the columns above and below the bridge elevation indicated the large magnitude of the local collision forces. After inspection, it was found that at least 4.5 inches of relative displacement must have occurred at least twice during the earthquake. The building also experienced extensive window glass cracking and falling, but whether pounding was the primary cause is uncertain. This building is classified as having Type-1 damage and possibly Type-2 damage as well.

Franklin Street, Oakland City Center: The building is 10 stories and constructed of reinforced concrete with a post-tensioned concrete floor system

(Fig. 6(a), building at right). It was built in 1965. This building pounded with an older 7 story building whose lower 4 stories are composed of reinforced concrete, and its upper 3 stories are of steel construction (Fig. 6(a), building at left). The buildings have about 2 inch separation.

The 10 story building suffered significant damage. Its lateral load capacity deteriorated due to severe damage at the slab-to-column connections. The horizontally placed reinforcing bars for the spandrel masonry walls were pulled out from the adjacent columns. Further study is needed to determine whether this damage is attributed to pounding. However, pounding caused the seismic hazard of falling building debris. Fig. 6(b) shows the debris that fell on and through the canopy located at the 2nd floor level. The brick veneer at the boundary of the two buildings was damaged due to impact, and a large amount of falling debris destroyed the canopy. This is classified as Type-2 damage and possibly Type-1 damage as well.

13th Street, Oakland City Center: The building is 11 stories plus a 2 story penthouse constructed of masonry combined with a steel skeleton. It was built in 1904. The building pounded between its 9th and 10th floors with the roof of an adjacent reinforced concrete parking structure (Fig. 7(a)) built in 1957. The buildings have about 2 inches wall-to-wall separation, but wooden formwork remained in this gap thus reducing the separation between the two buildings.

Pounding damage was observed along the entire contact length. Fig. 7(b) shows the location of severe pounding damage. The stairway is enclosed by the wall which pounded at the roof level of the parking structure. Since the stairway lacks a floor diaphragm at the pounding region, the wall was impacted and buckled out-of-plane (Fig. 7(b)). The stairway then collapsed at the pounding level and fell onto the lower levels, resulting in complete loss of the stairway. The pounding damage is classified Type-1 with incipient Type-2 damage.

11th Street, Oakland City Center. - The building is a large 6 story steel structure occupying an entire city block (Fig. 8(a)). It was built in 1981. The building in plan, consists of three segments separated by 4 inch expansion joints. All building segments have steel moment resisting frame systems. One segment was originally designed as a 20 story high-rise building, but only the bottom 6 story portion is presently constructed (this is the portion shown in the lower right corner of Fig. 8(a)). Accordingly, this segment is laterally much stiffer than the other two segments.

Due to the earthquake, these segments pounded at their floor slabs which are at common elevations. The slabs at the upper floors were locally damaged due to the contact forces, but there was no structural damage to the building. In general, pounding produces sharp irregular motions which results in large high frequency lateral accelerations (Kasai et al. 1990). It is possible that such accelerations contributed to other damage observed in the building. The windows facing the atrium fell down, and the computer equipments shifted and/or turned over. Heavy building equipments in the penthouse shifted significantly (Fig. 8(b)). Further, the plumbing for the fire protection system lacked seismic joints, and consequently it was destroyed at the building separations due to building relative motions. A considerable amount of water was released. The damage was quickly repaired and the separation distance between the slabs were increased. The pounding damage to this building is classified Types-2, 3 and 4.

Bluxome Street, San Francisco: - The building is a 4 story masonry structure having a large floor area. It was built in 1922. The building is located adjacent to a relatively modern 3 story reinforced concrete storage building having nearly the same floor area (Fig. 9(a)). The exterior walls of these buildings have virtually no separation. The building pounded at the roof level of the adjacent building, and the wall above the pounding level collapsed (Fig. 9(a)). The clear pattern of damage above the pounding level suggests that pounding may have contributed to this catastrophic event. As Fig. 9(b) shows, the cars parking on the street were completely crushed by the large amount of falling bricks and 5 people were killed. This case is classified as Type-1 and 2 damage.

CURRENT RESEARCH

The writers are conducting analytical research into pounding, sample references of which are listed below. The objectives are: to study the dynamics of pounding via correlative computer analyses of actual pounding incidents; to develop and provide engineers with practical analytical tools for predicting pounding response and damage; and to investigate possible methods of mitigating the damage due to pounding.

CONCLUSION

The Loma Prieta earthquake resulted in pounding between many buildings over a wide geographical area. The reported cases of pounding are concentrated in high density population areas of cities where maximum land usage is sought thereby promoting minimal building separations. Most incidents of poundings involved older multi-story buildings of masonry construction. Such buildings often have virtually no building separations.

It should be noted that the predominant architectural and/or structural damage of a minor nature (Type-4) is likely to be precursors to the more serious damage types (Types-1, 2, 3) that will occur during future more severe earthquakes affecting the area. It is imperative that rational methods be developed to mitigate the pounding hazard. The solution must involve major public policy regulations as well as research into the physical aspects of the problem such that practical engineering remedies can be formulated.

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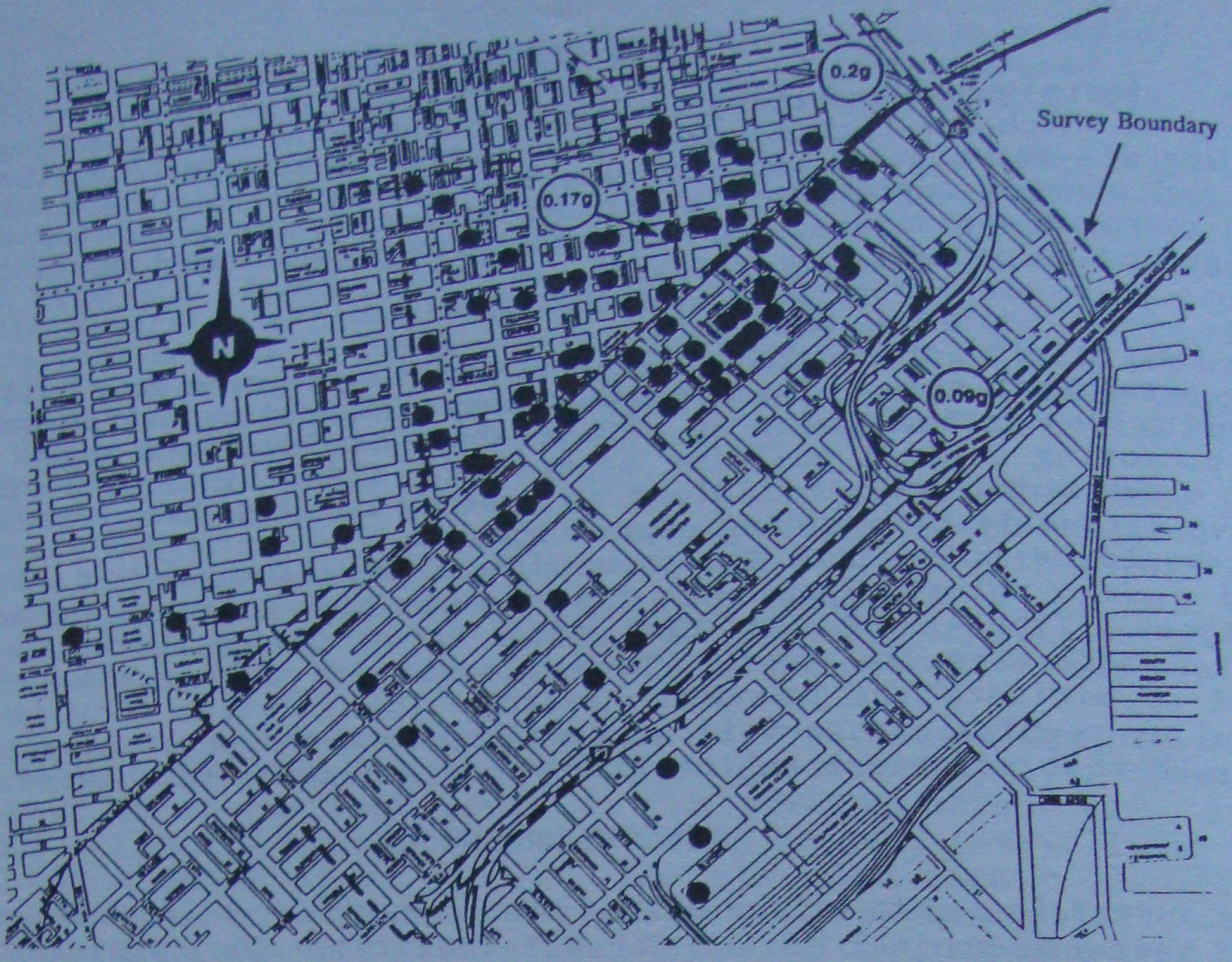


Fig. 1 Distribution of pounding damage in San Francisco Financial District and South-of-Market area.

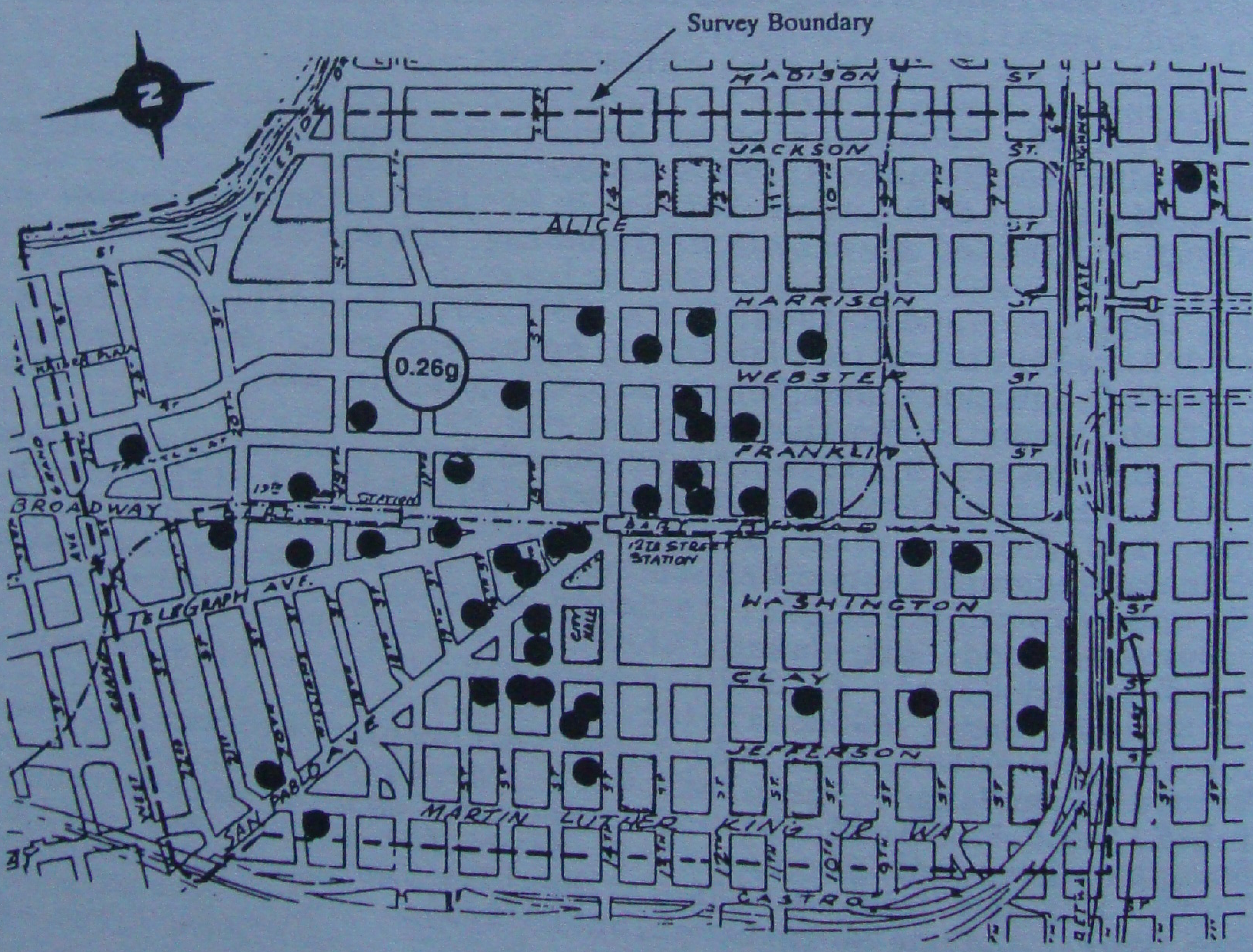


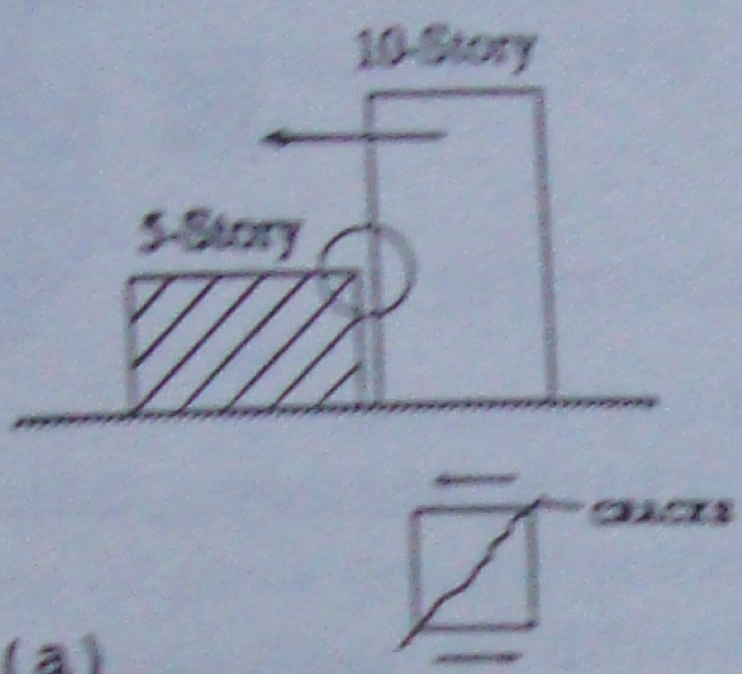
Fig. 2 Distribution of pounding damage in Oakland City Center.

(a)

(b)

Fig. 3 Damaged corner buildings in San Francisco Marina district.

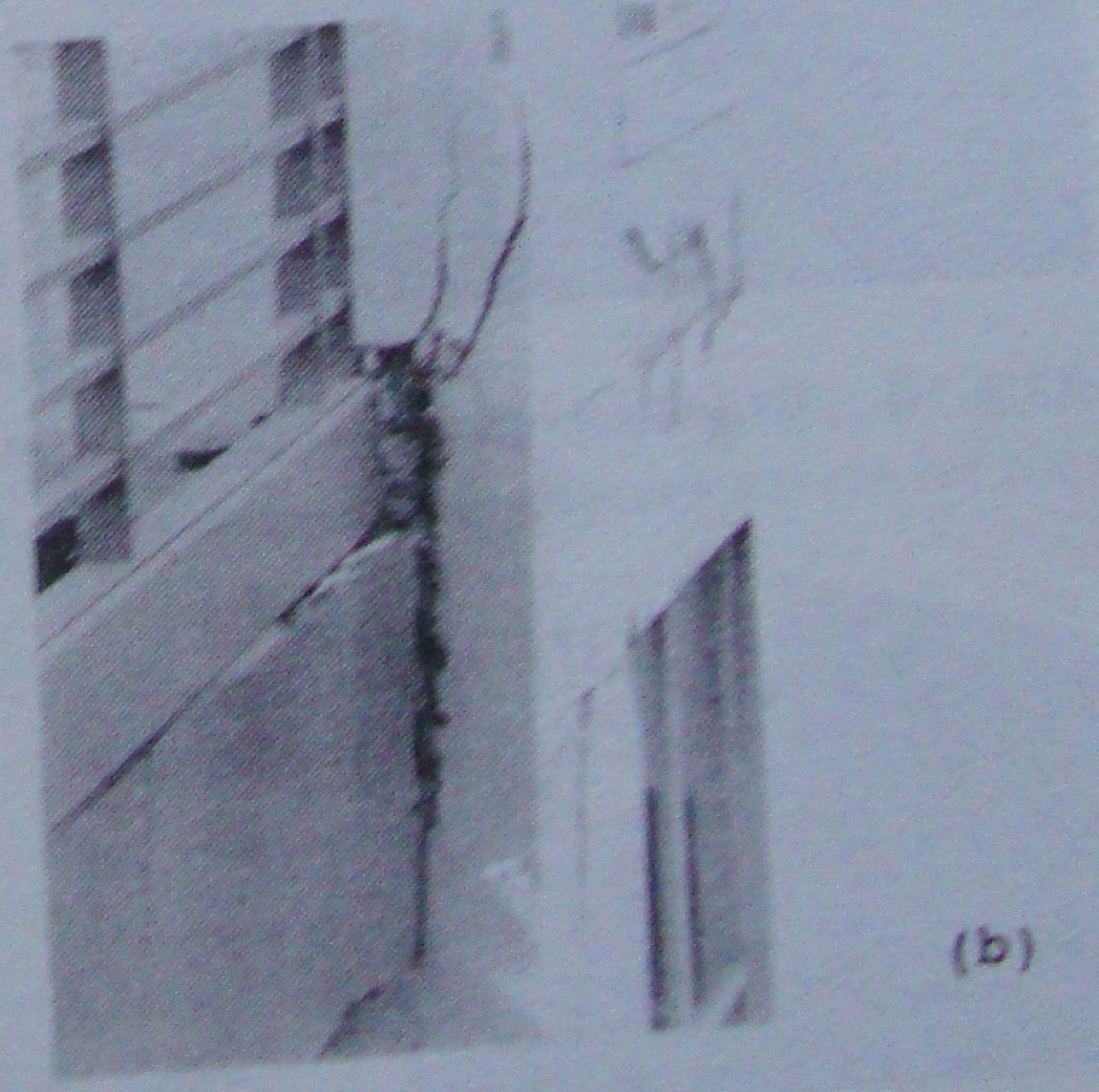
(a)



(b)

Fig. 4 Example pounding damage (Mission Street, San Francisco)

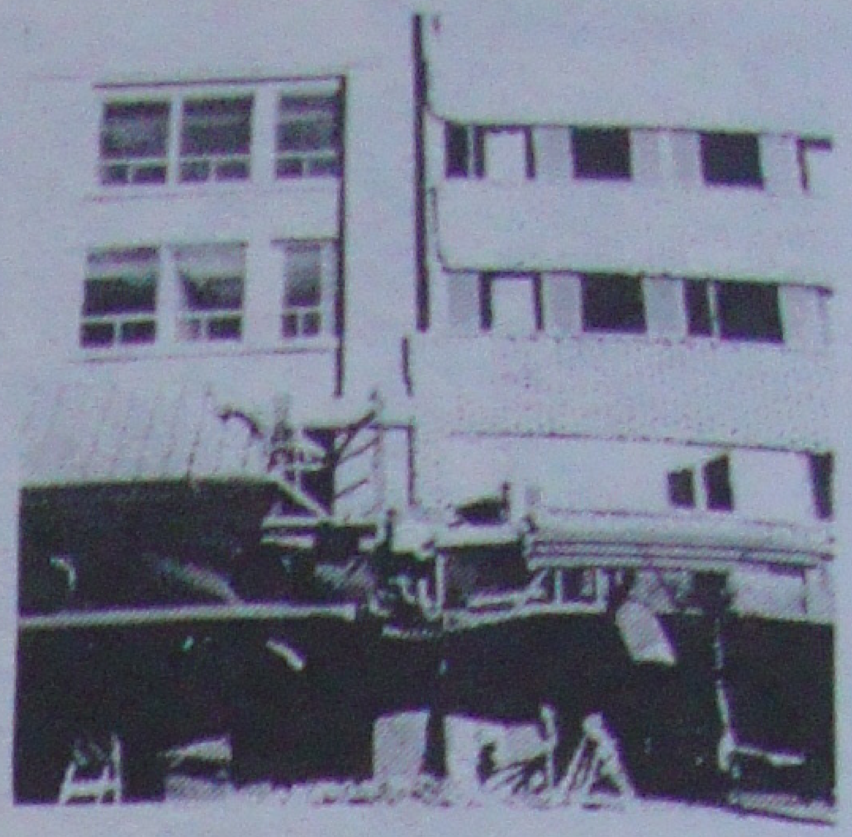
(a)



(b)

Fig. 5 Example pounding damage (Broadway Street, Oakland)

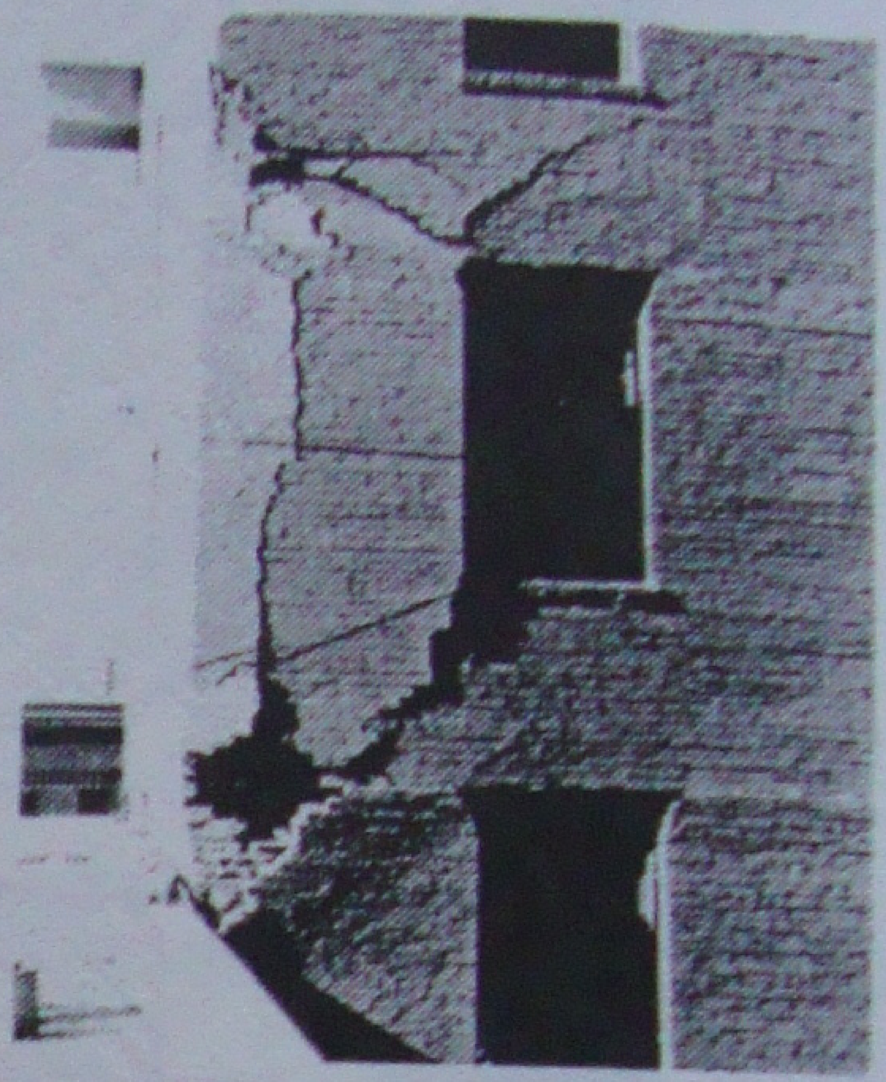
(a)



(b)

Fig. 6 Example pounding damage (Franklin Street, Oakland)

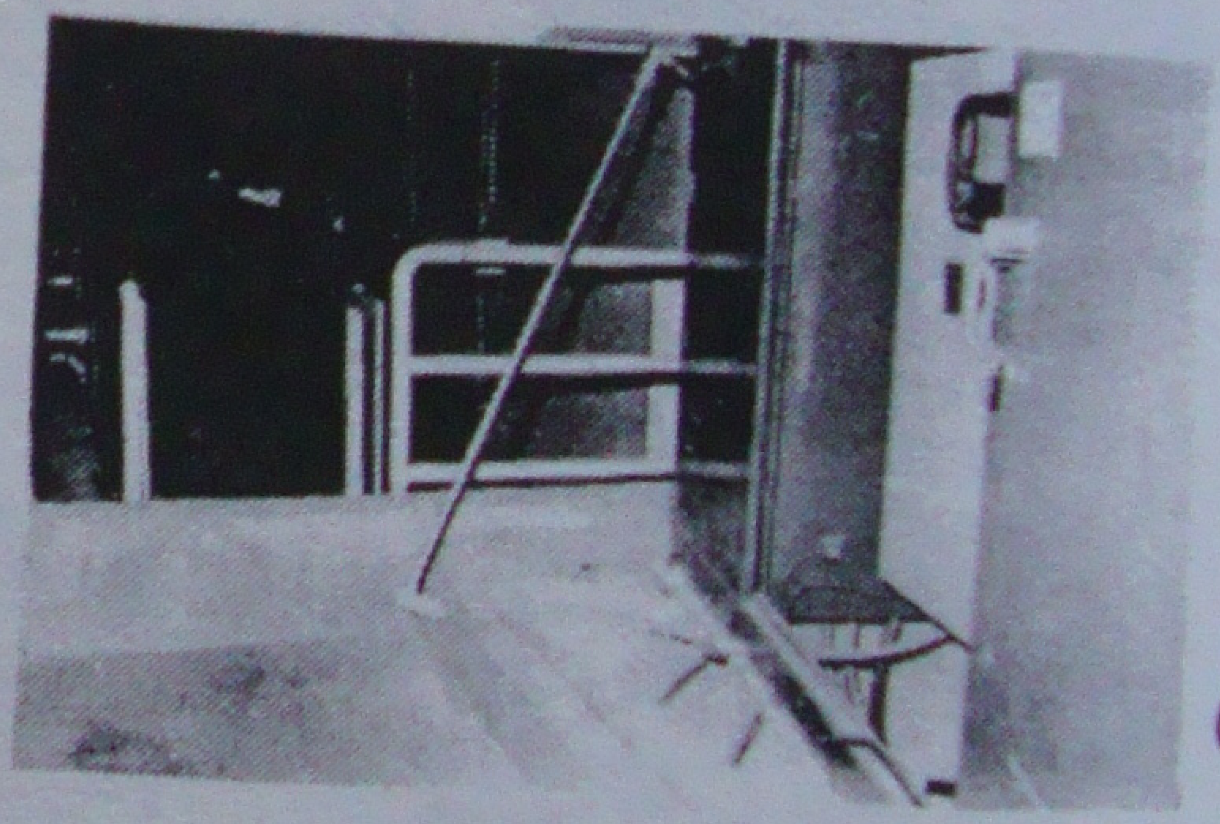
(a)



(b)

Fig. 7 Example pounding damage (13th Street, Oakland City Center)

(a)



(b)

Fig. 8 Example pounding damage (11th Street, Oakland City Center)

(a)

(b)

Fig. 9 Example pounding damage (Bluxome Street, San Francisco)