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Observed effectiveness of minimal seismic strengthening of unreinforced masonry buildings

D. R. Bonneville & D.W.Cocke
H.J.Degenkolb Associates, Engineers, San Francisco, Calif., USA

ABSTRACT: Thousands of unreinforced masonry buildings throughout the United States will be subjected only to moderate earthquakes in their usable lifetimes. In such cases, a minimal level of seismic upgrade, including such elements as parapet bracing and wall-to-diaphragm anchorage, can have a significant effect on the building's life-safety performance. San Francisco's parapet ordinance, enacted in 1976, provided a unique opportunity to study this issue on a large scale when the City was subjected to the 1989 Loma Prieta earthquake. Based on first-hand observations after the earthquake of San Francisco's posted Red-Tagged buildings (those most severely damaged), a study has been conducted that demonstrates the effectiveness of partial upgrade measures. It is concluded that many buildings with a minimal level of upgrade would have suffered partial or full collapse if they had not been upgraded, or if they had been subjected to seismic forces of greater intensity or longer duration. Thus, the effectiveness of minimal strengthening in areas of moderate seismic intensity is demonstrated.

1 INTRODUCTION

Unreinforced masonry buildings (UMBs) have performed poorly in every damaging earthquake and are generally considered to represent the foremost threat to life-safety. Since the mitigation of the UMB hazard will have a major financial impact on numerous building owners and will be disruptive to housing and historic building use, various alternative levels of seismic upgrade are being considered. While buildings in areas of high seismicity, such as California, require comprehensive upgrade schemes to assure life-safety protection, damage observations indicate that more limited measures may be appropriate in moderate seismic zones.

In this study, the effectiveness of limited strengthening measures is evaluated by reviewing the actual seismic performance characteristics of the 66 UMBs in San Francisco that were red-tagged after the 1989 Loma Prieta earthquake. Through this on-site review process, two objectives were undertaken: first, the effectiveness of the San Francisco Parapet Safety Program was evaluated based on its only real test to date; and second, the apparent effectiveness of slightly more extensive measures was assessed. Although San Francisco, an area of high seismicity, provided the setting for these observations, they are intended to apply to moderate seismic zones for which an earthquake of Loma Prieta intensity is the largest expected.

San Francisco's Parapet Safety Program was enacted in 1976. At the time of the Loma Prieta earthquake, hundreds of UMBs in the City had been retrofit under the parapet ordinance while hundreds of others were not upgraded (or not effectively upgraded) at that point. The parapet ordinance, which relates to all pre-1949 buildings, requires bracing of UMB parapets having excessive height to thickness ratios which may fall onto sidewalks and occupied spaces. In addition to bracing, it requires that the tops of walls be tied into the roof diaphragm to prevent out-of-plane failures. The Loma Prieta earthquake provided the first real opportunity to assess the effectiveness of the program.

The authors served as consultants to the City of San Francisco in assessing the emergency shoring needs of red-tagged buildings following the Loma Prieta earthquake. This provided the opportunity to closely inspect the condition of all heavily damaged buildings, including 66 UMBs. Those first-hand observations comprise the most significant aspect of this study as compared with other studies which are based primarily on statistical evaluation or analytical assessment.

The observations and discussions in this paper are limited to unreinforced masonry bearing wall buildings. Buildings with steel frames and unreinforced masonry infill walls are not discussed.

2 FACTORS AFFECTING UMB PERFORMANCE

Figure 1 shows the a map of the downtown area of San Francisco in which most of the City's UMBs are located. Also outlined on the map is the zone in which the Parapet Safety Program had generally been enforced at the time of the earthquake. The buildings are located on sites ranging in soil quality from rock to bay mud. Figure 1 indicates that most of buildings are located within the area of the city that was in compliance with the parapet safety program at the time of the earthquake. However, because the program is limited in general to parapets that can fall onto streets, sidewalks or occupied spaces, and because City and State owned buildings have generally not been included in the program, there were actually more UMBs subject to parapet (and upper wall) collapse than would be apparent from the map.

Since UMBs were rarely constructed with adequate seismic resistance, their performance in large earthquakes has been directly influenced by the extent to which they have been upgraded. Figure 2 shows a partial view of a typical UMB. The seismic strengthening elements that would be required for compliance with the San Francisco Parapet Safety Program are shown. As discussed above, this includes both bracing of the parapet and out-of-plane anchorage of the upper portion of the wall. A more comprehensive seismic upgrade, as required in a high seismic zone, would also include wall to floor

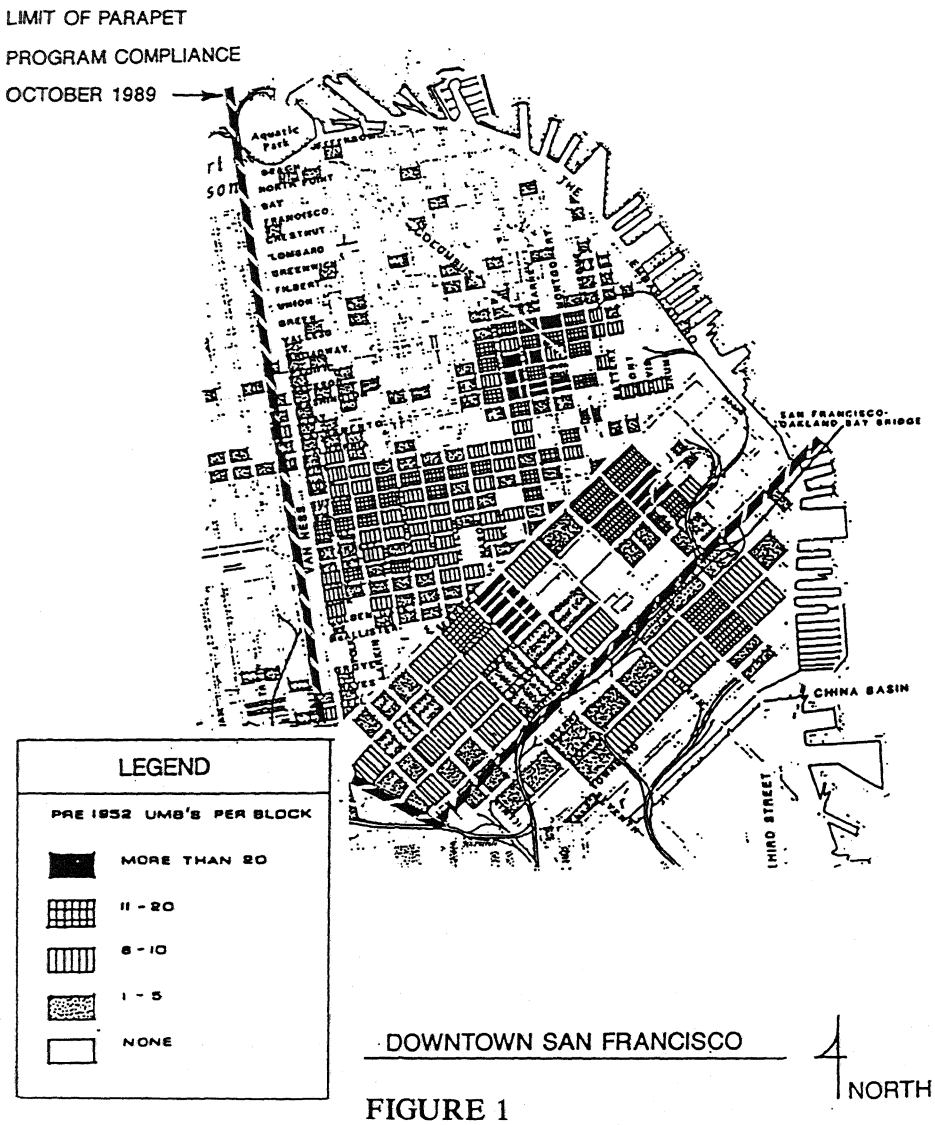
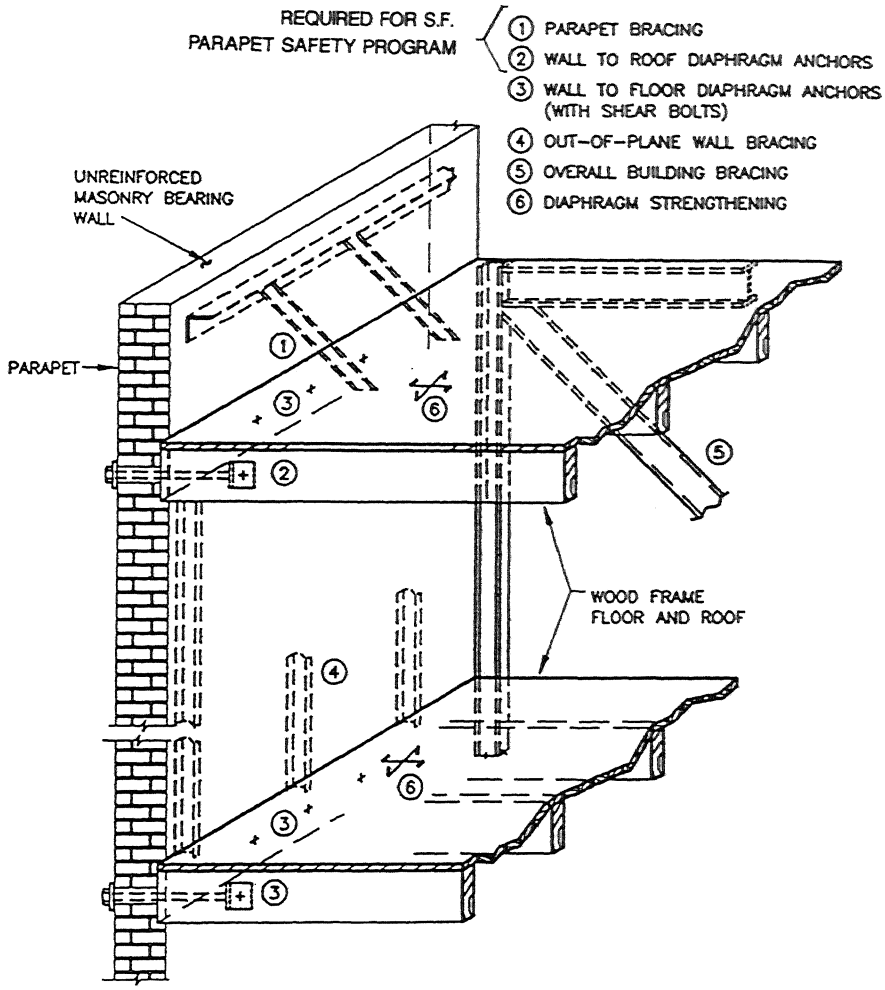


FIGURE 1



SEISMIC STRENGTHENING ELEMENTS FOR UMB'S.

FIGURE 2

diaphragm anchorage and may include out-of-plane wall bracing, diaphragm bracing, and building bracing, such as shear walls or braced frames. These items are also shown in Figure 2.

Based on observations of past seismic performance of UMBs, the strengthening elements shown in Figure 2 may be prioritized in terms of effectiveness. Generally, the priorities are listed in the following order:

1 Parapet Bracing (including wall to roof diaphragm anchorage)

2 Out-of-plane wall to floor diaphragm anchorage (including shear bolts)

3 Out-of-plane wall bracing

4 Shear wall strengthening (in-plane)

5 Diaphragm strengthening

Observations of UMB performance in San Francisco in the Loma Prieta earthquake generally confirm the appropriateness of the above order.

Although parapet bracing would not be a complete solution in itself in a high seismic zone, its position as the highest priority element is easily demonstrated based on both performance and theory. This is due to the fact that accelerations are highest at the upper level of the building, the fact that cantilever elements are subject to greater amplification, and the tendency for out-of-plane anchorage to be a weak link in most UMB construction.

3 JUDGING THE EFFECTIVENESS OF THE PARAPET SAFETY PROGRAM

Based on the document entitled,ATC-20 Procedures for Postearthquake Safety Evaluation of Buildings, sixty-six unreinforced masonry buildings in San Francisco were red-tagged due to severe damage caused by the Loma Prieta earthquake. The San Francisco emergency shoring program, developed in response to the event by building officials and their consultants, was based on the premise that emergency demolition should be used only as a last resort. Demolition was requested only where buildings were judged to be in a state of imminent collapse and where emergency shoring would not be effective or where it installation would endanger the lives of construction workers. This had the primary effect of preserving, to a large extent, the City's stock of historic buildings and it had the secondary effect of permitting detailed observation of seismic behavior.

Of the 66 red-tagged UMBs, 51 are included in the City's list as being in compliance with the 1976 Parapet Safety Program, although some have been judged, based on close observation, as not fully meeting the intent of the requirements. To facilitate evaluation process, the damage observed in the group of 66 buildings has been summarized within seven categories:

1 Parapet Collapse
2 Wall-Diaphragm Separation
3 In-plane Wall Cracking in Top Story
4 In-plane Wall Cracking in Other Stories
5 Out-of-plane Wall Failure
6 Other (Foundations, Wall Leaning, Etc.)
7 Collapse of Floor or Roof Framing

Table 1 indicates the number of buildings that exhibited each type of damage, and separates those buildings in compliance with the Parapet Safety Program from those not (or apparently not) in compliance. In numerous cases, the writers, based on actual observations, have judged that the building did not meet the parapet bracing program requirements, although the building is listed as in compliance with the program. Those buildings have been listed in this study as not in compliance. As shown in Table 1, none of the 50 buildings that complied with the ordinance at the time of the earthquake suffered parapet collapse. On the other hand, of the 16 buildings which were not in apparent compliance, 3 suffered collapse of a parapet. Thus, for the moderate intensity Loma Prieta earthquake, parapet bracing was apparently effective in

Building Damage Categories	With Parapet Bracing	Without Parapet Bracing
Buildings with Red Tags	50	16
Buildings with Parapet Collapse	0	3
Buildings with Wall-Diaphragm Separation	9	6
Buildings with In-Plane Cracking of Walls (Top Story)	36	11
Buildings with In-Plane Cracking of Walls (Other Stories)	39	12
Buildings with Out-of-Plane Failure of Walls	4	3
Other Damage	16	4
Collapse (Loss of Floor or Roof Framing)	0	0

TABLE 1: Effectiveness of parapet bracing on the seismic performance of sixty six red-tagged UMB's (Loma Prieta Earthquake).

mitigating a potentially serious life-safety hazard. This is consistent with actual field observations. Also noteworthy from Table 1 is an apparent tendency for parapet bracing to minimize out-of-plane wall failure, which contributes significantly to the cost of damage repair and was a major reason why demolition was considered as the most viable option after the earthquake by owners of buildings with that type of damage.

Although Table 1 does not demonstrate the tendency for parapet bracing to minimize wall to diaphragm separation, the numbers are somewhat misleading. For the 9 buildings included under this category, the wall to diaphragm separation had generally occurred along side walls which did not require bracing under the ordinance. Others had separated at levels below the roof. In other cases, the wall to roof diaphragm ties that accompanied the parapet bracing did not provide a tight enough hold on the wall, allowing outward movement of an inch or less. In general, for walls in which the bracing and anchorage was adequately installed, the out-of-plane separation problem was effectively eliminated.

Other damage categories listed in Table 1, are related to in-plane and out-of-plane failure of the masonry walls themselves, which are not directly affected by parapet bracing.

In general, parapet bracing was found to be very effective damage mitigation measure, particularly relative to life-safety protection. In spite of the 2,000 unreinforced masonry parapets in the city, there were very few cases of collapse and none for buildings which were properly in compliance with the ordinance.

4 JUDGING THE EFFECTIVENESS OF OTHER LIMITED UPGRADE MEASURES

Among the proposals currently under consideration in San Francisco for mandatory seismic upgrade of unreinforced masonry buildings, is a system known as "bolts-plus". Referring to Figure 2, the elements utilized in the bolts-plus level include parapet bracing (including wall-to-roof diaphragm anchorage), wall-to-floor diaphragm anchorage, and out-of-plane wall bracing as required. Although this system does not represent a complete seismic upgrade for all UMBs, it is a logical extension beyond simple parapet bracing, considering the UMB seismic upgrade priorities discussed earlier. Thus, its effectiveness relative to moderate earthquakes is worth consideration. This was done by projecting (or estimating) the damage that would have occurred in the same group of 66 buildings, assuming a bolts-plus upgrade had been in place at the time of the earthquake.

The similarity of the bolts-plus provisions to the parapet safety provisions permit a reasonable degree of accuracy in the damage projections. For example, neither of these limited measures improve the building's overall shear capacity. Therefore, any exhibited tendency toward shear cracking in the walls would not be directly affected. Other judgments required for these projections include the condition of the building materials and the detailing of both the lateral and vertical load systems.

Considering the same seven damage categories listed in Table 1, for parapet bracing effectiveness, the damage associated with each building, assuming a bolt-plus upgrade was projected. On this basis, it is estimated that, in addition to preventing parapet collapse, this system would have completely eliminated the 9 cases of wall-diaphragm separation and the 4 cases of out-of-plane wall failure. Thus, for a moderate intensity earthquake, such as Loma Prieta, the advantages of the bolts-plus system are apparent. This is due to the fact that wall anchorage is provided on all walls at all levels, rather than only the roof level at walls endangering streets and sidewalks and to the additional strength provided by the wall bracing elements.

5 CONCLUSIONS

The San Francisco Parapet Safety Program was found to be very effective as a life-safety protection measure in the Loma Prieta earthquake. Most of the heavily damaged UMBs were located in areas where the Parapet Safety Program had been enforced. None of the buildings which had adequate parapet bracing suffered collapse of any portion of the exterior brick walls, in spite of the heavy structural damage they incurred. Conversely, partial collapse occurred in 3 of the 16 buildings without parapet bracing.

In moderate earthquakes, limited seismic strengthening of UMBs may be an effective approach. For example, in the Loma Prieta earthquake it is projected, based on observations, that no collapse would have occurred if all UMBs had undergone the equivalent of a "bolts-plus" strengthening.

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