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Performance of high technology industries in the Loma Prieta earthquake

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ABSTRACT: The recovery of a region in the aftermath of an earthquake will be highly dependent on the recovery of its business and industry. Despite their value, little information is available in the public domain regarding the economic recovery and post earthquake recovery of such facilities. Nowhere is such information more lacking than in the high technology sector. The Loma Prieta earthquake, effecting a region densely populated with high technology industrial facilities, provided a unique opportunity to gather valuable information regarding the performance and post earthquake recovery of such enterprises. Of the 500 buildings surveyed 14 suffered damage with repair costs in excess of $200,000. Most of these were out of operation for months following the earthquake. Data centers generally performed well, however, special vulnerabilities were highlighted by the earthquake. Case studies of the damaged facilities showed that special design standards and construction inspection requirements are needed to protect business from losses associated with downtime after an earthquake.

1 INTRODUCTION

The vitality of a region in the aftermath of an earthquake will be highly dependent on the recovery of its business and industry. The jobs, tax base and vital cash flow they provide fuel both regional and national economies. Despite their economic value, little attention has been focused on the development and implementation of standards to control post earthquake disruptions to business and industry. One of the reasons for the absence of such standards is the lack of information in the public domain regarding the actual performance of such facilities in earthquakes. Information regarding downtime and costs to restore business operations has generally not been publicly disclosed.

Nowhere is post earthquake information more lacking than in the high technology sector. The complexity of high technology building systems, often coupled with extreme investment in contents, increases their susceptibility to financial losses in earthquakes. Fierce competition among firms has limited the amount of damage information publicly disclosed.

The Loma Prieta earthquake effected a geographic region densely populated with high technology industrial facilities. Silicon Valley, the semiconductor capital of the United States, is located approximately 30 miles from the epicenter of the Magnitude 7.1 earthquake. Computer and chip manufacturers, defense contractors and biotechnology firms located in Silicon Valley experienced the event. This event provided a unique and valuable opportunity to collect information on the earthquake performance of high technology facilities. Of particular value was the opportunity to gain insight into the relationship between damage to buildings and contents and the restoration of business activities. Collected data was used to assess the adequacy of current and past design and construction practices to limit post earthquake business disruptions. Information on cost of repairs, downtime, and financial losses due to business interruption was gathered to assist business owners in understanding the consequences of earthquake damage and setting earthquake performance standards appropriate for their facilities.

2 DATA COLLECTION

Seven corporations located in Silicon Valley provided data for this study. Information on over 500 facilities was collected. Each respondent was asked to complete a data collection form for each building in his company's inventory. Ninety completed data collection forms were received. Information on other buildings was gathered from interviews with numerous corporate representatives.

The buildings included in this survey were constructed between 1942 and 1989, most between 1964 and 1985.

Building sizes ranged between 10,000 square feet and 560,000 square feet. Several types of construction were represented in the survey sample - approximately 50 percent of the buildings were of tilt-up construction, 37 percent were steel framed structures with lateral force resisting systems of either steel bracing or moment resisting frames, and the remainder of the buildings were reinforced masonry, wood or a combination of systems. None of the facilities were of unreinforced masonry construction.

The performance of data processing centers was examined through the results of an in-house post earthquake damage survey conducted by a major computer manufacturer. The results of this study, made available for this research project, included a survey of 11 data processing facilities located in the San Francisco Bay Area.

3 REPORTED EARTHQUAKE DAMAGE

Consistent with the relatively low level and duration of earthquake shaking in Silicon Valley, reported damage was generally minor. Most facilities experienced damage to nonstructural items including suspended ceilings and lighting fixtures, furnishings, piping, and equipment. Most facilities were closed for one day during which time an inspection of the facility was conducted and clean up took place.

The damage to fourteen of the buildings included in this study caused repair costs in excess of $200,000. Most of these buildings were out of operation for months. A summary of the building characteristics and reported damage for each building is given in Table 1. Each is briefly described below.

Building 1 - This building was designed and constructed prior to modern requirements for tilt-up construction. Earthquake damage occurred at the connection between the glued-laminated roof framing girders and the reinforced concrete pilasters. Cracking and spalling of the pilaster at this location was caused by a lack of confining reinforcement around the cast-in-place anchors which provided connection between the glulam beams and pilasters. Because the facility housed a distribution center critical to the company's business operations, prompt restoration of operations was critical. Prearrangements with a structural engineering firm and contractor permitted immediate post-earthquake assistance. Within five days of the earthquake, the roof-wall connections were repaired and strengthened and the facility was reoccupied. The cost of remedial work was $200,000.

Building 2 - During the Loma Prieta earthquake, a portion of a window wall was dislodged. The window wall, lacking anchorage to structural framing overhead, experienced excessive movement out of plane. While appropriate connection to structural framing was specified in the construction documents, the connections were not installed. Concurrent with the dislocation of the window wall, sprayed-on fireproofing materials containing asbestos were dislodged, the suspended ceiling was damaged, and the facility was contaminated by the asbestos release. Restoration activities, including removal of all asbestos materials, took six months and cost $1 million.

Building 3 - Corporate headquarters for a multi-billion dollar enterprise are housed within this two-story steel moment resisting frame building. During the earthquake, numerous leaks occurred at hot water couplings in reheat coils located in overhead ductwork. Water was released throughout the facility. Dislodged ceiling framing and tiles, broken windows, and damage to roof flashing at expansion joints were also reported. Most pipe leaks were repaired within one day after the earthquake. Additional repairs and fortifications took place in the subsequent months while the building was occupied. Total repair costs were $1 million.

Building 4 - This two-story administration building, leased by a large Silicon Valley corporation, suffered substantial structural and nonstructural damage. The lateral force resisting system for the building consisted of tilt-up walls at the ends of the building in the transverse direction and steel braced fames in the longitudinal direction. After the earthquake, a large crack was observed in the second floor concrete diaphragm at a discontinuity caused by the presence of a stair opening. After investigation, it was found that the chord bars called for in the diaphragm at this location were missing. The flexibility of the resultant building caused substantial damage to nonstructural elements including ceilings, ductwork, piping, furnishings and glazing. The building was closed for nine months during which time a detailed investigation of the building was conducted to assess as-built conditions. Several construction deficiencies were identified and repaired and the steel braced frames were strengthened before this building was reoccupied. The total cost born by the building owner was not available. The tenant cost for relocating building occupants was reported as $1 million.

Buildings 5,6,7 - These two-story research and development buildings, leased by a large Silicon Valley firm, were of nearly identical construction to Building 4 previously discussed. During the earthquake, the steel bracing members which provided lateral resistance in the longitudinal direction buckled. The slenderness of these bracing members varied from 110 to 160. A detailed seismic evaluation of the buildings was conducted after the earthquake. Various repair and upgrading measures were developed. The owner chose to strengthen all steel bracing and bracing connections prior to reoccupancy. Bracing repairs and upgrading were completed nine months after the earthquake. The total cost to the building owner is not known. The cost to the building tenant due to relocation of activities was estimated to be $1 million for each building.

TABLE 1

BUILDING	STRUCTURE	NO. STORIES	YEAR CONSTRUCTED	AREA	$ TO RESTORE(1)	PERCENT DAMAGE(2)	TIME TO RESTORE OPERATIONS	PRIMARY DAMAGE
1	Tilt Up	1	1975	194,000 SF (18,023 SM)	$200K	2%	5 Days	Weakened Roof-wall Connection
2	Steel	2	1968	51,000 SF (4,738 SM)	$1M	20%	6 Months	Dislodged Window Wall
3	Steel	2	1980	478,000 SF (44,408 SM)	$1M	2%	1 Day	Damaged Piping, Ceilings
4	Steel	2	1973	27,200 SF (2,527 SM)	$1M	37%	9 Months	Concrete Floor Crack
5	Steel	2	1973	29,918 SF (2,779 SM)	$1M	33%	9 Months	Buckled Steel Bracing
6	Steel	2	1973	31,500 SF (2,926 SM)	$1M	32%	9 Months	Buckled Steel Bracing
7	Steel	2	1973	30,000 SF (2,787 SM)	$1M	33%	9 Months	Buckled Steel Bracing
8	Steel	4	1970s	NA	NA	NA	12 Months	Broken Sprinkler Piping
9	Steel	2	1985	220,000 SF (20,439 SM)	$6M	23%	5 Months	Buckled Steel Bracing
10	Tilt Up	2	1962	67,580 SF (6,278 SM)	$6M	89%	18 Months	Cracked Concrete Walls
11	Tilt Up	1	1947	110,000 SF (10,219 SM)	$40M(3)	600%	3 Months	Failed Roof Truss
12	Precast	3	1980	44,500 SF (4,134 SM)	NA	NA	3 Months	Movement Between Walls and Floor
13	Steel	2	1971	96,000 (8,919 SM)	$4M	42%	6 Months	Asbestos Release
14	Steel	2	1983	80,700 (7,497 SM)	NA	NA	3 Weeks	Radioactive Contamination

(1) Includes cost of relocation, repair, and, if performed, seismic upgrading

(2) Estimate based on assumed square footage construction costs

(3) Includes $20 million of business interruption losses

Analytical studies were conducted to corroborate the observed earthquake damage (1, 2). Static and dynamic analyses were conducted using both linear elastic and inelastic models of the steel braced frames as designed and as retrofitted for improved performance. Various retrofitting schemes were examined to determine their performance in providing both strength and drift control under 1991 Uniform Building Code forces and under recorded ground motions. Braced frames redesigned according to the requirements of the 1991 Uniform Building Code were shown to experience inelastic deformations, including buckling and tension yielding of braces, when subjected to ground motions from several Loma Prieta earthquake records. The analytical studies further demonstrated the difficulty of providing both strength and drift control for even relatively simple structures which must meet operational demands during and after an earthquake.

Building 8 - Broken sprinkler lines in the uppermost floor caused water to infiltrate all floors and all areas of this four-story office building. The breaks in the sprinkler lines occurred at connections between main horizontal piping runs and vertical drops which extended 1 to 2 feet below. The pipe drop reportedly extended through cable trays. The movement of the suspended, unbraced cable trays caused the connections of the sprinkler lines to weaken and fail. The building was evacuated and remained out of operation for a period of twelve months after the earthquake. The facility was repaired and extensively remodeled during this time and records were recovered through dehydration techniques. Restoration costs were not reported.

Building 9 - A research and development laboratory was housed within this two-story, steel braced frame building which included interstitial floors. The building, square donut shaped in plan, included steel braced frames located around the building for resistance to lateral forces in both directions. Many of the braced frames included braces which were interrupted by floor framing at the interstitial level. During the earthquake, several of the interstitial beams twisted due to a lack of lateral restraint at the location of bracing connections. Because these braces were no longer capable of resisting additional force, other braced frames were overloaded, resulting in buckled bracing and failed welded connections. Building occupants were evacuated and relocated. Extensive demolition was required to expose all bracing members and connections for inspection. Seismic improvements, including the installation of lateral restraining members at the locations of instability within the braced frames, were implemented. The building was reoccupied five months after the earthquake. The reported costs for repairs and relocation of personnel was estimated to be $6 million.

Building 10 - This two-story, tilt-up building housed research and development operations for a large Silicon Valley corporation. The building, constructed in 1962, lacked the diaphragm, wall and collector strength required by modern codes. During the earthquake, several of the reinforced concrete walls cracked causing concern and discomfort among building occupants. Because the lateral force resisting system was weakened, the owner chose to evacuate the building and relocate its occupants. A detailed seismic evaluation of the building was conducted and recommendations for seismic strengthening of the facility were proposed. Seismic strengthening measures were designed to increase the lateral force resistance of the building to that required by the 1988 Uniform Building Code. The design included new steel braced frames at the building perimeter, new reinforced concrete walls at the interior, and new chords and collector members. Strengthening was completed eighteen months after the earthquake. Reported costs for the seismic improvements and relocation totaled $6 million.

Building 11 - A machine shop critical to the production line of a large defense contractor was housed in a 1942 wood frame building with metal siding. The roof was framed with longspan bowstring trusses. During the earthquake, the lower chord of many of the trusses failed at the inter-connection of web framing members. Diagonals and verticals which framed into the lower chord did not have a common work point. The eccentricities caused by this configuration caused wood splitting and tension failures in the bottom chord under earthquake loading.

Distress in the roof framing system led to evacuation of the building and suspension of all production operations. In order to restore operations, an adjacent building was evacuated to supply needed space for the machine shop. Most of the shop was then relocated; equipment was recalibrated and safety checked. Some equipment which could not be relocated was left in place and a portion of the original building was shored around it. The remainder of the damaged building was demolished. Production was stopped for a period of three months. Costs for building demolition, shoring, relocation of personnel and equipment, calibration of all equipment, and leasing additional facilities were reported as $20 million. An additional $20 million was reported as business disruption expense. This sum includes all of the overhead expenses (salaries, benefits, real estate costs, etc.) paid during the three-month period while they had a lapse in production.

Building 12 - The structural system of this building combined cast-in-place, reinforced concrete walls with a precast floor system. After the earthquake, movement along the wall-floor connections was observed. Further investigation revealed that the dowels designed to transfer force between the floor diaphragm and walls had not been installed. The building was evacuated and repaired during a three-month period following the earthquake. Cost of repair and relocation was not reported.

Building 13 - This building was constructed with a steel moment resisting frame. The sprayed on fireproofing contained asbestos which was shaken loose during the earthquake. The suspended ceiling framing was severely damaged during the earthquake and the asbestos was released throughout the building. Overturned filing cabinets containing corporate records were contaminated with the asbestos. Clean up and decontamination took weeks and cost approximately $4 million.

Building 14 - Radioactive tracers fell off laboratory tables to the floor, releasing radioactive materials into this building. Operations were suspended for three weeks during decontamination.

4 SUMMARY OF EARTHQUAKE DAMAGE

Of the nine buildings with reported structural damage, substantial downtime was generally experienced. Long operational interruptions resulted from the length of time needed to procure structural engineering services and conduct a thorough investigation of the extent of damage, examine repair options, prepare construction documents, hire a contractor, and implement remedial measures. In addition, most owners of buildings structurally damaged in this moderate event acknowledged the likelihood of a larger seismic event effecting their site in the future. Consequently, seismic upgrading accompanied most earthquake repairs. Implementation of structural repairs and upgrading coupled with subsequent remodeling or reinstallation of architectural and nonstructural systems required months for completion.

Financial losses due to business interruptions were generally minor in this study because most damaged facilities housed operations which could be conducted elsewhere. For example, administration and most research and development activities were relocated and continued to function offsite. However, at one location where damage occurred in a facility vital to production, $20 million of business interruption losses were reported as a result of three months of downtime.

Measures which could have prevented observed earthquake damage include enhanced jobsite observation and inspection of both structural and nonstructural elements during construction. In addition, peer review of designs prior to construction would likely have avoided damage to one of the facilities. Damage to older buildings could have been avoided by conducting seismic evaluations of the facilities prior to the earthquake and correcting the deficiencies identified. Implementation of upgrading measures to prevent loss of function could also have been undertaken.

5 DAMAGE TO DATA PROCESSING CENTERS

In general, damage to data processing equipment was minor in the twelve facilities examined. Most equipment was moved back into place and operated without problems when power was restored. Eleven out of several hundred machines included in the survey failed to come on-line once power was restored after the earthquake.

The biggest problem observed was machine movement. Some machine damage occurred due to movement. Machines mounted on casters and some mounted on levelers moved several feet. Light duty levelers failed and allowed machines to drop onto casters and roll. Many machines moved far enough to drop a caster or leveler into a cable hole. Formed wire caster clips were not adequate to hold machines in place except on the ground floor or in areas of very minor vibration inputs. Machines jumped the clips and rolled until they went into a cable hole or were restrained by their cables. The lack of mechanical strain reliefs at the box entry point allowed the strain of stopping the motion to be placed on the cable and connector resulting in damage to the cable or connector.

Additional items which were observed to cause problems with data processing equipment included installations in upper stories of buildings where higher motions were experienced, stacked units or units on shelves not secured, location of cable holes too close to casters or levelers, loss of power, falling ceiling tiles, and damage to water lines for air conditioners or sprinklers. At two locations, power distribution units were observed rolling into cable holes, coming to rest on 60 amp power lines. Had these cable ruptured, serious damage could have occurred.

Observation at the sites visited showed that certain conditions, design features and installation methods tended to reduce the problems. These measures included: data centers in basements or on first floors, limiting the amount of machine movement, use of lockable casters or sturdy levelers, cable hole protection, restraining table top units, use of raised floors reinforced for earthquake loads, cable strain reliefs to protect cables, careful attention to cooling water, electrical power, phone lines and sprinkler systems, and readily accessible power switches and water valves in the computer installations easily identified and operable before and after the earthquake.

6 CONCLUSIONS

1. Potential losses associated with business interruption after an earthquake should be considered when selecting criteria for design and retrofit of buildings.

2. Minor earthquake damage may impair operations and lead to substantial costs in loss of time and revenues. If structural damage is involved and engineering services or outside contractors are needed, the time to resume normal operations is generally extended considerably.

3. Construction deficiencies in either structural or nonstructural systems can lead to earthquake damage resulting in substantial downtime. Careful jobsite inspection is needed where prompt resumption of business activities is an earthquake performance objective.

4. While data centers are vulnerable to earthquake damage, many problems can be minimized by careful installation practices.

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