

EARTHQUAKES. A NEW LOOK AT CRACKED MASONRY

RANDOLPH LANGENBACH

Economics, fears of liability and a strict damaged-buildings repairs ordinance have contributed to an extensive delay in the repair of masonry-infill buildings in earthquake-stricken Oakland, Calif. This delay has had a devastating impact on the economic well-being of Oakland's downtown. Three years later, several of the most significant historic downtown office buildings remain abandoned and threatened with demolition. Here is an alternative to expensive conventional retrofits used on two buildings in Oakland.

On the day following the October 1989 Loma Prieta earthquake, a visit to downtown Oakland, Calif. seemed anticlimactic. Except for the flattened freeway, the damage was subtle. Some engineers expressed disappointment in not finding the "widespread devastation" reported in the news. The visible damage—a pile of broken glass here, a crack there, and some broken masonry scattered around—could not foretell the true catastrophe that has evolved since that October afternoon.

Surprisingly, most of the city's older unreinforced brick buildings came through with little damage. In fact, Oakland has become the first U.S. city in earthquake history to suffer extensive damage, not to its older unreinforced brick buildings but to its major early 20th century steel- and concrete-frame downtown buildings. Oakland's 18-story City Hall (built in 1912), along with about 15 other major downtown multistory buildings, remains closed.

Following the Loma Prieta earthquake, Oakland enacted the Damaged Building Repairs Ordinance, which prevents owners from repairing the damage. Instead, any structure that, according to a specific engineering analytical procedure, has lost "over 10% of its pre-earthquake lateral capacity" must be upgraded to a slightly modified

version of the 1988 Uniform Building Code (UBC) at what is often an enormous cost. The standard, static procedures of the UBC have proven economically incompatible with infill-frame construction. Indeed, the costs of upgrading this type of building to the UBC vastly exceeds the equity value of many of the properties, preventing most of the owners of damaged buildings from repairing and reopening their buildings.

The results of this policy are now clear. During the three years following the earthquake, only three of the 24 downtown buildings that were closed have been upgraded and reopened. Nothing has been done to the 12 large office buildings with infill-frame construction. Even City Hall remains closed. After extensive study by as many as eight engineering firms, plans are moving ahead on its retrofit, estimated to cost about \$70 million. The intended public safety goal has not been achieved, and the economy of central Oakland has been seriously damaged.

The invention of the skyscraper in Chicago during the 1880s prompted a move from bearing-wall masonry construction to the use of a steel (and, later, concrete) frames. Consequently, the vertical load-carrying structure of the larger commercial buildings shifted from massive bearing walls to a lightweight network of steel columns and

beams. Masonry, however, did not cease to play a significant structural role. Engineers relied on masonry cladding to stabilize and stiffen the structures against wind and earthquakes. The collapse of frame and infill wall structures during an earthquake has not been a problem in the U.S.

So far, in upgrading the damaged buildings, the approach has been to remove and replace as much of the masonry as possible. The Hotel Oakland stands as a dramatic example of the possible risks of this plan. This building was partially strengthened prior to the earthquake. To save costs, the upgrade was to less than full code, but the building was "reinforced to prevent collapse and to minimize life safety hazards in a major earthquake" ("Quake-Safe Housing, Again," CE September 1991). All interior clay tile partitions were removed and replaced by studs and plasterboard.

When the earthquake struck, the hotel was the only frame building from which large pieces of the masonry facade dropped onto the sidewalk below. The upgrade prevented a building collapse, but this was not the primary issue. No building of this type collapsed in the earthquake. That this partially retrofitted building sustained considerably more damage to its facade than any of the unstrengthened buildings is signifi-

cant. The removal of the masonry partitions may have contributed to the damage because without them, all of the loads had to be carried by the remaining masonry of the exterior facade.

NEEDED: A RATIONAL APPROACH

The UBC is written for new building construction, not for rehabilitation. Unreinforced masonry is not allowed. Rather than giving the masonry the structural credit it is due (as part of an integrated system working together with the boundary steel frame), the code encourages engineers to treat it only as dead load, or to use very conservative values for its strength. Consequently, many engineers retrofit structures by shifting most or all of the earthquake forces from the infill masonry to new steel or concrete braces or shear walls. This requires braces and walls that are both strong and stiff enough to prevent the masonry from cracking. This cannot be done economically.

As Robert Englekirk and Thomas Sabol wrote in "Strengthening Buildings to a Life Safety Criterion" (*Earthquake Spectra*, volume 7, No.

1, 1991): "The code procedure does not lend itself to the separation of the damage level criterion from collapse level criterion and, as a consequence, does not allow the flexibility usually required in rehabilitation work. This is one reason why the statement 'bringing it up to code' is essentially meaningless when one refers to seismic rehabilitation."

Archaic building materials should not be evaluated in isolation from the total structural system. While unreinforced masonry is brittle, its postelastic behavior as part of a system contributes greatly to a building's earthquake resistance. In other words, the whole is more than the sum of its parts. The object of any strengthening effort should be directed toward providing a backup system that adds ductility, reduces the risk of falling debris hazards and prevents any possibility of collapse.

The problem with infill-frame buildings is not the cracks, but the possibility of destruc-



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tive and life-threatening degradation and collapse of the infill walls. Masonry cracking cannot be prevented. This is not antithetical to the building code. The code assumes postelastic behavior even of new buildings during major earthquake. When masonry begins to crack, two beneficial events occur: (1) The resonance of the structure changes, moving it out of phase with the earthquake shaking (i.e., a softening up of the building); and (2) the cracking of the masonry adds damping without serious risk to the building's vertical load-carrying ability.

Collapse is unlikely because the surrounding steel or concrete frame works to confine the cracking masonry. In turn, it is the masonry that continues to prevent the steel (or the nonductile concrete) frame from collapsing. When the first infill panel cracks, the load is immediately shifted to another panel, which then exceeds its elastic limit and cracks. As the shaking contin-

ues, more masonry becomes cracked before the original cracked panel can attract more load. In this way, the energy of an earthquake spreads throughout a wide area of a building's facade and internal walls.

Further distortion of the frame causes the cracked masonry to become loaded in compression, forming an equivalent diagonal strut. In panels with windows the strut is formed in the spandrel. The compressive strength of the masonry, loaded in this way, is usually far greater than the elastic limit of the shear capacity of the panel at the onset of the earthquake. While masonry in shear resists 50–150 psi, in compression it can resist 1,000–3,000 psi. So the onset of cracking within the masonry panels is only the first step in the building's response to the earthquake. It is not "failure" of the wall.

Two repair and strengthening projects are based on these principles. The Oakland Medical Building and the Woodrow Hotel were damaged sufficiently to be subject to the city's ordinance. The Oakland Medical Building is a 10-story, nonductile reinforced concrete infill-frame office building constructed about 1920. The Woodrow Hotel is a seven-story, steel infill frame with timber floors constructed in 1912, and was later run as a low-rent, single-room-occupancy hotel. Because of damage from the quake, the city shut it down. Since that time it has been vandalized, and a repair and retrofit project has yet to be carried out.

The city did not close the Oakland Medical Building; its retrofit is under construction. The first estimates for bringing it to code were in the range of \$1.5 million–\$2 million (\$30–\$40 per square foot)—far more than would have been economically feasible. James Hill and Associates, Signal Hill, Calif., completed the current structural design, based on performance, rather than current code-based force criteria. It is currently under construction for less than \$500,000 (\$8–\$9 per square foot).

The approval process for this alternative design required six months in plan check and a full owner-financed peer review. It un-

derwent intense scrutiny by the city's public works department, despite the fact that no other seismic upgrade of an earthquake-damaged downtown office building had yet gone forward using conventional methods. So far, it is the only damaged downtown office building to be upgraded.

The design is based on controlling the building's deflection to an acceptable level in a major earthquake. Its objective is to use fully the building's existing lateral capacity. The design is based on the computed response of the building evaluated together with a detailed analysis of the existing materials. The designers used the building's response to the Loma Prieta earthquake to validate the computer modeling of the structural behavior. By approaching the design in this way, they can avoid the use of conventional code-based equivalent lateral load and its associated prescriptive standards. The final repair consisted of a single shear wall in the transverse direction. In the long direction, the designers determined that the repair and strengthening of a damaged two-story exterior wall was sufficient.

USING DAMPERS

For the Woodrow Hotel, two conventional static-based engineering designs for repair and retrofit were carried through to working drawings before the alternative proposed by our team could be developed. Unfortunately, this project has not gone forward beyond the design stage, partly because the enormous costs originally estimated for the conventional designs have so discouraged the owner.

The Loma Prieta earthquake cracked the brick masonry on the rear of the building, but left no damage on the street facades. The complete lack of damage to the Woodrow's two front walls was surprising, considering the large window area. There are probably two explanations: (1) Since the masonry of the front walls stops at the second floor, with open storefronts below, the resulting "soft story" helped isolate the masonry above from earthquake forces; or (2) the large openings above break the shear walls of masonry into a spandrel and pier system capable of larger story drifts, and cause inelastic flexural movement of the piers capable of leaving no visible marks. In this way, the brick spandrel braces the steel frame, and protects the brick piers between the windows from being excessively damaged by the bending of the steel column.

The first retrofit design, approved by the city, called for the replacement of one

wythe of brick with concrete over most of the exterior. This would have altered the building beyond recognition, at an estimated cost of about \$1.5 million. That design was rejected as impractical. A second design, by the same engineer, called for four complete two-bay-wide steel-braced frames on the inside of the exterior walls extending from basement to roof.

I began investigating a concept of energy-dissipating design and beneficial use of the soft story as a means of avoiding future damage to the facades under a grant from the California Preservation Foundation, with Lerner & Nathan Architects of San Francisco. Rather than adding rigid braces to protect the building from collapse of the soft story, I proposed to decouple the building from ground motion by allowing it to sway and to add restraints.

A chance meeting with James M. Kelly, professor of engineering at the University of California, Berkeley, led to the idea of using viscoelastic dampers in the restraints. Kelly had pioneered research on base isolation as a form of earthquake-resistant construction, and had recently begun a study of systems that introduce damping into the building superstructure itself.

The dampers are made by 3M Corp. They have been used for more than 25 years to reduce building vibrations caused by high winds. They consist of steel plates coated with a proprietary acrylic copolymer material that have viscous as well as elastic behavior when stressed in shear. These sandwiched plates are installed on new diagonal braces. Because no storefronts exist in the rear, the strengthening design must account for the transfer of more forces through that wall. The torsional movement of the building will be kept under control by the damped frames in front. The flexible floors allow the front and rear walls to be treated differently.

The logic is simple. If the front of the building was protected during Loma Prieta by the soft story, the dampers would avoid defeating this protective feature in a subsequent earthquake. At the same time, the braces would overcome any possibility of collapse. The dampers also have the advantage of providing significant nondestructive damping, activated at the onset of the earthquake. They are engineered precisely and introduce a known amount of damping at the onset of shaking. They do not require large deformations before the plastic behavior begins, and they have a set maxi-

mum drift limit.

While the dampers can reduce the earthquake damage to the masonry above, we still must discover how to accommodate these computed forces on masonry that is in excess of its elastic limit. In other words, the dampers can provide an excellent way to limit damage to the structure, but they cannot fulfill the prescriptive requirements of the building code to infill-frame buildings. The only solution to this dilemma is to change the building code to fit the building. Until a specific new building code for infill-frame buildings is devised (research for this is under way), economy in construction will require a performance-based design and extensive engineering design work for each project.

As we strengthen these early 20th century buildings, using sophisticated computers and other technological breakthroughs, there is a strong tendency to view pre-building-code structures with a degree of arrogance. This attitude blinds us to their inherent strengths. People of the past, with more limited means, used their creative powers to solve the same problems we face now.

Designers chose masonry to perform as part of the structural systems of buildings constructed immediately after the most massive earthquake the country had yet experienced—the 1906 San Francisco earthquake. In the case of the new masonry-clad San Francisco City Hall, which was built to replace a structure that had collapsed, the engineer specified "[n]o ... diagonal bracing ... below the second floor in order that the necessary flexibility against earthquakes should be retained." Now officials are proposing to retrofit this same city hall, damaged in the Loma Prieta quake exactly as predicted, with a base-isolation scheme costing \$130 million.

The notion that cracks in masonry constitute "failure" is a common misunderstanding that has emerged in the engineering profession, mainly, perhaps, from the analysis of reinforced concrete, where cracks can signify vulnerability to collapse. As a result, many important and substantial historic buildings are at risk. ◊

Randolph Langenbach, a building conservation specialist and former professor of architecture at the University of California, Berkeley, is now a technical consultant for the Federal Emergency Management Agency, San Francisco.