History of Shotcrete in Seismic Retrofit in California

by James Warner

The widespread use of structural shotcrete actually began long before the first application was made. Its rise was politically motivated and its continued development dictated by the occurrence of earthquakes. Responding to a school fire in the 1920s, the Los Angeles School Board directed that all future school buildings be constructed of masonry. However, masonry of the day was not reinforced, and several hundreds of these buildings were destroyed or damaged in the great Long Beach earthquake of 1933. Fortunately, the quake occurred in the early morning hours when the schools were unoccupied; had it been during the day, hundreds of deaths and thousands of injuries would have likely resulted.

Within a month of the event, the California State Legislature passed the Field Act, which set up the Office of the State Architect (OSA). All new hospitals and schools were to come under jurisdiction of this new authority that adopted generally more stringent requirements for design and construction standards than the existing codes. The act also required the seismic strengthening of all remaining masonry school buildings. With some 70 buildings destroyed and more than 400 damaged by the earthquake, this new agency had a Herculean task to undertake. The work was interrupted by World War II, but resumed in earnest following victory in 1945, with literally dozens of major projects each year until 1976 when all pre-1933 buildings not strengthened were to be abandoned.

Shotcrete was an ideal method for the reinforcement as it could be easily performed in the existing buildings regardless of access. Further, it would bond well to the existing concrete and masonry. At that time, only the dry-mix gunite process was available, and it was still subject to the proprietary interests of the Allentown Pneumatic Gun Company. There were four licensees in the Los Angeles area, and they formed the Gunite Contractors Association in 1951 to set quality standards and promote the process. These four contractors performed virtually all of the Field Act work and maintained rigid quality in their operations. They set the quality standard for the next several decades, during which time the performance requirements were continually raised with every subsequent earthquake.

Initially, the work involved the application of a thin membrane of reinforced shotcrete over the existing masonry surfaces. A wythe of brick was usually removed around the boundary area of openings, the surface abrasive blasted, and a network of relatively light reinforcing consisting of No. 3 and 4 bars on approximately 18 in. (0.45 m) centers, placed, as shown in Fig. 1. One or more larger bars were placed around the boundaries and 3 in. (76 mm) of new shotcrete was applied.

Fig. 1: Minimal reinforcing and fairly thin shotcrete augmentations were common in early seismic retrofit

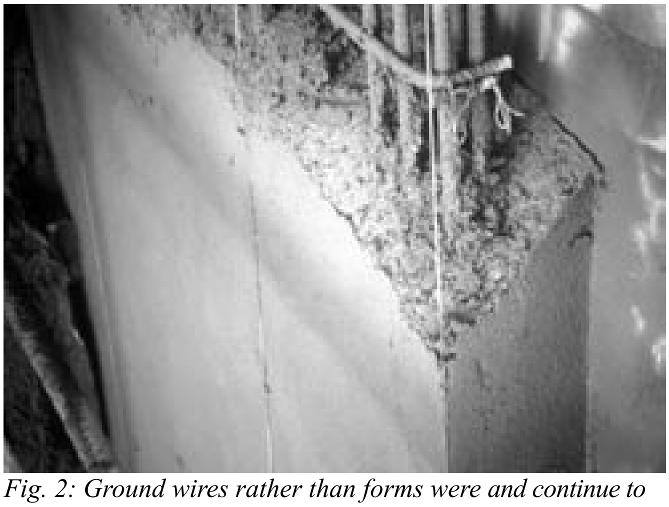

Fig. 2: Ground wires rather than forms were and continue to be used for maximum nozzle access

Rebound tended to gather in the boundary recesses, so a blow man was used to direct a blast of compressed air to clear rebound from the work. Because forms at corners and around the openings added to rebound entrapment, they were eliminated and ground wires were used to provide alignment control for the finishers, as shown in Fig. 2. The work was performed in this manner until 1952.

The 1952 Tehachapi earthquake occurred in the early morning, so again there were few casualties. However, schools not yet strengthened suffered significant damage, and even some that had been strengthened were damaged. This resulted in upgrading the design standards, primarily by increasing the size and amount of reinforcing, often using two layers, and also increasing the thickness of the new shotcrete. Boundary recesses were enlarged, similar thickened ribs throughout a wall area were sometimes used, and floor areas penetrated as shown in Fig. 3, to provide continuity for the augmentation. More and larger bars were added to the boundary and rib recesses as well.

The local telephone company had also suffered damage in the quake and set about a major program to strengthen its facilities. Unlike schools, these were often of concrete construction. They also tended to be more confined with small and often congested working areas, and the work usually called for even heavier reinforcing and thicker augmentations. Abrasive blasting was not as effective as with brick substrates, so chipping of the concrete surfaces was required as were steel tie dowels grouted into drilled holes.

To thoroughly encase the now large and congested reinforcing, the nozzleman was required to shoot at a multitude of different angles; in the process, the amount of rebound increased significantly. Nevertheless, the work continued, as did the high-quality performance. To maintain the quality, however, the rate of placement suffered and large amounts of rebound occurred. A good day might find 30 yd^3 (23 m^3) of material going through the gun, but as much as 40% was wasted as rebound.

The 1950s found an increasing use of the newer rotary gunite machine, but the contractors and their Gunite Contractors Association were adamant that it wouldn't provide the necessary quality for structural work. They became stubbornly resistant to any changes in the way things were done. To further their thinking, an impressive brochure was prepared. It gave the history of gunite and included many photographs of structural work, ending with a nonproprietary specification for structural gunite...almost nonproprietary, that is.

Fig. 3: Multiple reinforcing curtains and continuity between floors became common following the 1952 Tehachapi earthquake

Fig. 4: Typical shotcrete rig used for structural work prior to the mid-1970s

Under the section on equipment was a provision that application be made using an Allentown double-chamber pneumatic gun. This, of course, eliminated any operators with more productive rotary guns and directed virtually all structural work to the four members of the "club."

They continued with the double-chamber gun, usually mounted on four-wheel trailers that also contained a mixer and storage for the hoses and other tools, as shown in Fig. 4. Mixing was done with a standard skip-type, drum concrete mixer. It was typically mounted on inclined tracks so once it was on the job, it could be raised sufficiently to discharge directly into the gun. For the skip to be low enough to be filled by hand laborers on the ground, it was supported on tracks and raised with a piston air motor-powered winch. It was filled with concrete sand to guide bars denoting the correct quantity that was always based on the inclusion of even bags of cement.

During the 1960s, the threats to this group grew beyond the rotary gun with the development of the wet-mix process. Early on, wet-mix work was not of very good quality and its employment was generally limited to slope pavement and other minor uses. However, with the development of better pumps and an increased knowledge of mix design, it now threatened to elbow in on structural work. Unlike dry-mix, it did not require constant nozzle manipulation to complete mixing, allowing the nozzle to be more discretely directed for optimal placement in the increasingly thicker sections and congested reinforcing. Resulting rebound was significantly reduced, productivity greatly improved, and, of course, costs were lowered. It would only be a matter of time until this procedure would present major competition for structural work.

Then came the San Fernando earthquake of February 9, 1971. Major damage was done to structures of all types with hospitals particularly hard hit. This resulted in even more stringent requirements for structural strengthening. Both the thickness of new shotcrete sections and the amount of reinforcing were increased. Multiple layers of closely spaced bars became common, as did the use of numerous large bars (up to No. 14) around openings, boundaries, and other areas of high stress. Still, the dry-mix process was still firmly entrenched for structural work, so the amount of rebound increased even further (refer to Fig. 5). Along with this, productivity decreased with significant increases in the cost of the work. The wet-mix process became an ever greater threat after it was successfully used for strengthening of the California State Capitol in the early 1970s.

Fig. 5: Large amounts of rebound were produced, especially in cramped conditions with heavy reinforcing

Wet-mix shotcrete is subject to greater shrinkage than the traditional gunite. This became a particular problem where thick sections were to terminate against overhead surfaces in existing structures. It thus became common for application to stop immediately adjacent to the upper boundary, as illustrated in Fig. 6. The final closure would then be shot after the major shrinkage had taken place. In this regard, note the beveled surface of the original placement. Rebound has always tended to gather in isolated areas at the beginning of shooting, and this became an increasing peril as sections became thicker and more heavily reinforced. For this reason, beveled joints have been used from the very beginning to assure quality joints. Not withstanding the American Concrete Institute's guideline that construction joints subjected to compressive stress should be square, the beveled joints have worked well for more than 50 years and are certainly superior, if not requisite, to obtaining quality in structural applications.

The next major events were the Loma Prieta earthquake in 1989 and the Northridge event in 1994. Massive structural damage occurred followed by evermore stringent design standards and subsequent legislation requiring virtually all major structures to be strengthened. This, of course, meant more reinforcing to the point that proper placement and compaction of even regular concrete would be difficult (for example, Fig. 7). Again, shotcrete contractors rose to the challenge, as did their highly competent nozzlemen who now often positioned the nozzle within the reinforcing network itself to properly encapsulate the reinforcing steel, as illustrated in Fig. 8.

A particularly interesting aspect of the Northridge earthquake was observed in the collapse of a building with which I was involved in a previous retrofit. The remarkable ability of shotcrete to bond to existing substrates and previously placed layers has often been questioned, but no longer! When

Fig. 6: Final closure of massive placements stopped short of overhead with beveled face, to allow shrinkage prior to final closure

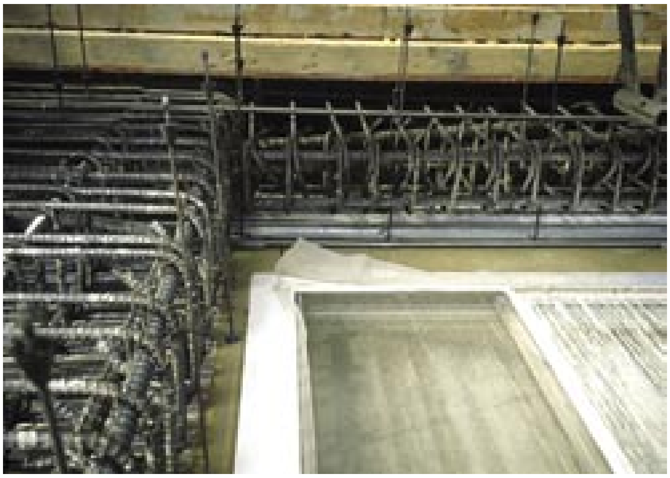

Fig. 7: The reinforcing for seismic retrofit continues to get larger and more congested

Fig. 8: Wet-mix process allows the nozzle to be held very close and even within the outer reinforcing to achieve complete encapsulation

Fig. 9: Shotcrete overlay literally slid down like a curtain as building collapsed

one end of the five-story Kaiser medical clinic collapsed, the upper portion of the shotcrete overlay merely came down as a sheet, as shown in Fig. 9. The original retrofit had been applied to the ends of existing brick infilled concrete frames, according to the standards of pre-1971, using the dry-mix process. Because the length of the structure was much greater than the width, it was strengthened in the transverse direction only. The failure was in the longitudinal direction, the strengthened ends being more resistant. Of great interest was the observation of the excellent quality of shotcrete bond to the original brick. The masonry wall disintegrated but the outer wythe remained strongly bonded to the shotcrete as illustrated in Fig. 10.

Fig. 10: The brick wall shattered but outer layer remained bonded to the shotcrete

Although the original "gunite players" adamantly resisted change and refused to recognize the validity of either the rotary gun or the wet-mix shotcrete process, the general procedures they developed continue to be valid to this day and remain requisite to obtaining good quality structural shotcrete, regardless of whether the dry-mix or wet-mix shotcrete process is used. With the now enormous amount of reinforcing commonplace, use of ground wires instead of forms is more important than ever. To limit the gathering of rebound and facilitate its removal, section buildup with a bevel both parallel and perpendicular to the shooting surface is mandatory. To guard against rebound buildup in subsequent layers, horizontal construction joints should be beveled. Also essential to the work quality, the blow man continues to be a necessary companion of the nozzleman at all times.

It appears that the amount of reinforcing in shotcrete has reached its limits, but this has occurred after each great seismic event. One must wonder what the next great quake will bring, but past experience suggests the shotcrete industry will be ready to take up whatever new challenges develop.

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