should be carefully selected so as not to damage the surface skin of shotcrete. Otherwise, form requirements are similar to conventional concrete.

5.3—Formwork

Forms may be of any rigid material, such as wood, steel, paper-backed reinforcing mesh, expanded metal lath or stable inflatable form (Fig. 5.1).

In all cases, the form should be adequately braced and secured to prevent excessive vibration or deflection during the placement of the shotcrete. All formwork should be designed to provide for the escape of compressed air and rebound during shotcreting. For column construction, two sides can be formed or the four corners can be formed using light narrow wood lath; satisfactory results may be obtained where three sides are formed, provided the width is at least two times the depth. Similarly, in beam construction, the soffit and one side may be formed, leaving the other sides open, or a light lath strip can be used to delineate the soffit corners. It should be braced or shored so that no deflection occurs under the impact and dead load of the fresh shotcrete. Nonload-bearing forms may be removed as soon as the shotcrete has achieved final set. Forms are generally not stripped for a few days to avoid superficial damage to the shotcrete. The crew should leave load-bearing forms in place until the shotcrete achieves sufficient strength to support the member. Form removal should be directed by the engineer or the decision to remove forms can be based on satisfactory field strength tests.

Fig. 5.1—Waterproofing panels used as back forms with wood as bottom forms.

5.4—Reinforcement

5.4.1 *General*—Reinforcement consisting of welded-wire reinforcement (mesh) or plain or deformed reinforcing bars is required in installations where shotcrete will be subject to structural loading. As a structural material, reinforcement in shotcrete is designed using the same criteria as in reinforced concrete. In those applications where shotcrete is not subject to or has limited structural loading, as with interior and exterior linings to 3 in. (75 mm) thickness or in concrete repair where bar reinforcement may already exist, reinforcement in the form of welded-wire reinforcement (mesh) or fibers is recommended. Wire reinforcement or fibers limit the development and depth of cracking resulting from shrinkage and temperature stresses.

Anchorage devices may be used with mesh, fiber-reinforced shotcrete, or both, to prevent debonding. Debonding may be caused by feather-edging, poor or nonuniform bond, deteriorating substrate, or overload. Well-proportioned shotcrete, properly placed against a structurally sound substrate, should not debond at the interface.

Reinforcing bars are rarely used in shotcrete with a thickness less than 1-1/2 in. (40 mm). Mesh may be used in thicknesses down to 1 in. (25 mm). For thin sections of shotcrete, properly sized and proportioned steel fibers may be successfully substituted for standard reinforcement. Using steel fibers in sections thinner than 1/2 in. (13 mm) is not recommended. Some steel fibers will cause some rust staining at the surface, which may effect the appearance of an exposed surface.

5.4.2 *Bar reinforcement*—Reinforcement obstructs the shotcrete material stream. Best results are usually obtained when the reinforcement is designed and positioned to cause the least interference with the placement of the shotcrete. The nozzle operator's skill becomes increasingly important to ensure adequate encasement of reinforcement as bar size increases or as spacing decreases. If larger-size bars are required by the design, the crew should take care to properly encase the bars with shotcrete (Section 8.5.8). With congested or large-size reinforcement, the crew should demonstrate that they have the experience to properly encase the reinforcement. Mock-up panels or documented previous experience on work of similar difficulty may demonstrate if the crew can properly encase the steel. In any case, reinforcement should be sized, spaced, and arranged to facilitate the placement of shotcrete and minimize the potential for development of sand pockets and voids. The minimum cover over reinforcement should comply with the job specification or applicable building codes and is usually based on environmental influences.

When existing reinforcing bars are encountered in concrete repair, corrosion products should be a minimum of three times larger than the maximum-size aggregate in the shotcrete. If possible, clearances around an exposed bar should be at least three times the maximum size of the largest aggregate particle in the shotcrete mixture.

Where possible, bars should be spaced to permit shooting at a slight angle from either side of the bar. If the design allows, direct contact of the reinforcing splices should be avoided. Non-contact lapped bars should have a minimum spacing of at least three times the diameter of the largest bar at the splice. For most shotcrete applications with thickness less than 6 in. (150 mm), one layer of reinforcement is usually sufficient, with or without mesh, depending on the application. For greater thickness using several layers of bars, the size and spacing of the bars should be carefully designed and installed for proper and effective shotcreting of deeper recesses. Where several layers of reinforcement are in place before shotcreting, the outermost layers should be sufficiently open to allow the nozzle clear, unobstructed access to the interior of the member (Fig. 5.1).

Fig. 5.2—Shooting through welded-wire mesh cut and bent to follow contours or repair.

Intersecting reinforcing bars should be rigidly tied to one another and to their anchors with 16 gauge (1.3 mm) or heavier tie wire and adequately supported to minimize vibration during shotcrete placement. Vibrations in the reinforcing steel can cause sagging of plastic shotcrete, create voids, and reduce in-place strengths. Large knots of tie wire should be avoided to minimize the formation of sand pockets and voids. Loose mill scale and rust and oil or other coatings that can reduce the bond of the shotcrete to the reinforcement should be removed.

5.4.3 *Steel mesh reinforcement*—The mesh should be cut to proper size and carefully bent to closely follow the contours of the areas to receive shotcrete (Fig. 5.2).

The reinforcing mesh should be securely tied with 16 gauge (1.3 mm) or heavier tie wire to preset anchors or reinforcing bars. Large knots of tie wire should be avoided to minimize the formation of sand pockets and voids. When sheets of mesh intersect, they should be lapped at least 1.5 spaces in both directions and be securely fastened. In no case should the wires be spaced less than 2 in. (50 mm) apart (Section 5.4.2). When more than one layer of mesh is required, the first layer may be covered with shotcrete before placing the second layer. Some type of anchor or tie should extend to the second layer. Unless the design dictates otherwise, the sheet of mesh should be placed in the center of the shotcrete layer.

5.5—Anchors

Special devices are used in shotcrete work to anchor, support, or space the reinforcement. Some of the factors involved in determining the type, size, and spacing of these devices are: the type of application; its design; the shotcrete thickness; the nature of the original surface; and the type, weight, and geometry of the reinforcement. The maximum recommended spacing of anchors for most applications is 36 in. (900 mm) on-centers-both-ways for horizontal surfaces, 24 in. (600 mm) on-centers-both-ways for vertical and inclined surfaces, and 18 in. (450 mm) on-centers-both-ways for overhead surfaces. If special conditions exist, the design of the anchor spacing and size should be checked for sufficiency in pullout and shear. Anchors or spacers for reinforcement should be located to provide sufficient clearance around the reinforcement, permit proper cover, and complete encasement with sound shotcrete. Special bowtie connectors are sometimes used with fiber-reinforced shotcretes to provide mechanical connection to the anchors.

5.5.1 *Anchoring to steel*—Reinforcement can be attached to steel surfaces using mechanical clips, blank nuts welded to the steel, stud-welded devices, slab bolsters, or self-tapping screws; by direct attachment; or by any manner that does not compromise the integrity of the structural member. Clips and bolsters are only used to directly attach mesh to steel. Studs or nuts can be used to attach reinforcing bars or mesh. Drilling holes through structural members to facilitate the anchoring of reinforcement should be avoided. Consult the structural engineer before drilling into structural members or before welding reinforcing steel.

5.5.2 *Anchoring to concrete, masonry, or rock*—Reinforcement can be attached to concrete, masonry, and rock surfaces using expansion anchor bolts, steel dowels, self-drilling fasteners, and expansion shields. The choice depends to a large degree on the application, type of specified reinforcement, position of work, number and size of anchors, and cost. The manufacturer's recommendations for size, depth of hole, and safe-working loads in shear and pullout should be explicitly followed.

Expansion anchor bolts are the most commonly used concrete anchors. They are available straight and threaded with a nut at the exposed end or without threads with a hooked or L-shaped exposed end. Both styles have some type of expanding sleeve or wedge on the embedded end to provide positive locking action in a predrilled hole. These anchors come in variable lengths so they can be adapted to shotcrete from 1-1/2 to 6 in. (40 to 150 mm) thick.

Self-drilling fasteners and expansion shields may be used and are useful for 6 in. (150 mm) and thicker layers, up nonuniform shotcrete sections, and where multiple layers of reinforcement are specified.

Steel dowels or reinforcing bars are used in structural shotcrete applications when sections are 6 in. (150 mm) or thicker, and heavy cages of reinforcing bars have to be supported and anchored. They are also used for anchoring shotcrete to rock. They should be set sufficiently deep to meet pullout criteria and installed using a nonshrink cementitious grout, epoxy, or polyester resin.

5.5.3 *Anchoring to wood*—Reinforcement may be attached to wood surfaces using individual bar chairs, slab bolsters (continuous chairs), or nails. They should be positioned to provide proper cover and encasement by the shotcrete. Bolster legs should be trimmed off when they are adjacent or parallel to reinforcement. If the wood surface is a removable form, nails should not be used and the chairs and bolsters should be plastic-tipped to eliminate rust on the formed surface. Reinforcing bars or individual wires in mesh should not coincide with the longitudinal wire of a slab bolster (Fig. 5.3).

5.6—Alignment control

Alignment control is necessary to establish line and grade in shotcrete construction and to ensure that proper and uniform