not well braced can be analyzed initially using a reduced flexural strength consistent with the maximum compressive strength that can be developed by existing lateral bracing and tension membrane resistance, depending on the existing connection strength, and including any effects from dead load. This analysis may show that the component is adequate to resist applied blast loads without failing, particularly for rebound response. The use of stiffeners to resist lateral torsional buckling should be considered for steel beams and girders with inadequate lateral bracing.

10.6 UPGRADES FOR METAL PANEL WALL AND ROOF SYSTEMS

Metal panel wall and roof systems consisting of corrugated metal panels and cold-formed wall girts and roof purlins are commonly used as exterior cladding. Metal panels are constructed of thin-gauge material that buckles in the compression flange at maximum moment regions before the panel cross section develops its ultimate plastic moment capacity. Resistance provided after buckling occurs in the maximum region is due to tension membrane response, which is characterized by stretching of the panel rather than flexure. This is described in Section 5.4.4. To achieve this type of response it is necessary to restrain the ends of the panel to provide the required in-plane reaction. A typical conventional design utilizes small self-drilling/tapping screws attached to base angles and wall girts to secure the panels in place. These screws are typically sufficient to develop enough membrane capacity to maintain the flexural resistance up to the maximum allowable deflection for low or medium damage. At larger deflections, the connections tend to fail due to tearout through the panel ends as well as pull-out over the head of the screws. Use of a flexible support will also limit the magnitude of load occurring at the ends of the member. This can be accomplished by developing a support which deforms in flexure and limits the end reaction. This type of connection is shown in Figure 10.5.

Reducing the span increases the capacity of metal panels in flexure. Since resistance is a function of the square of the span length, addition of intermittent

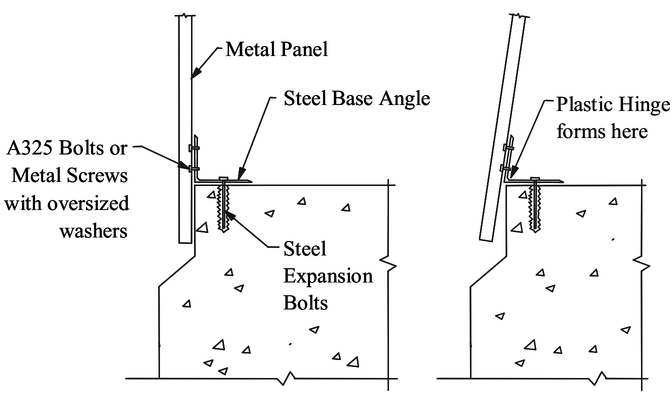

FIGURE 10.5: Base Angle Detail for Flexible Connection

supporting members can be very effective in increasing in blast capacity of panels. This can be accomplished by adding wall girts or roof purlins to the structure. This upgrade also increases the blast resistance of the supporting members since their tributary supported width is reduced. Cost for this upgrade can be quite high if the interior of the structural system is not easily accessible or if construction requires interruption of operations.

When strengthening of existing panels is not feasible, panels can be replaced with heavier gauge metal panels, two nested conventional panels, or specially designed blast resistant panels. There are also commercially available blast resistant panels that have been developed for protection against terrorist attacks. Girts and purlins can also be upgraded by replacing with a heavier member. These components can also be overlapped and connected so they act as a continuous component across interior supports. Typically, the girt or purlin connection must also be upgraded in these cases. Metal wall systems can also be upgraded with a blast resistant shield wall, as discussed in Section 10.8.

In some cases, large metal buildings with very low occupancy can be designed to resist blast loads using controlled release panels (*Oswald 2002*). Controlled release panels are conventional corrugated steel panels that are only continuous over one supporting member with limited strength connections to supporting members at the panel edges and a strong connection to the intermediate supporting member, so they fail by wrapping around the intermediate supporting member. These supporting members and the building framing can be designed for a lower blast load if controlled release panels are used because the failing panel transfers less blast load into the supporting members based on shock tube testing results. Attention must be devoted to securing interior building components and objects that can become hazardous debris due to interior blast loads. This upgrade with controlled release panels should only be considered when the free-field pressures will not directly cause serious injury to building occupants *Baker*.

Vent panels designed according to *NFPA 68* can be used to reduce blast loads from interior explosions of flammable materials. These panels can have restraint system (i.e. steel cable tethers) attached to the building framing so they do not become missile hazards.

10.7 UPGRADES FOR CONCRETE MASONRY UNIT (CMU) & CONCRETE WALLS

Many petrochemical structures include CMU walls with little or no steel reinforcement. This type of construction lacks ductility and has low resistance to blast loads. There are many ways to retrofit masonry walls to increase their blast resistance, including many that have been developed to resist blast loads from typical high explosive threats from terrorists. However, only a limited number of these retrofits have typically been considered practical for buildings subject to industrial explosion blast loads, which typically have much longer blast load durations than high explosives.

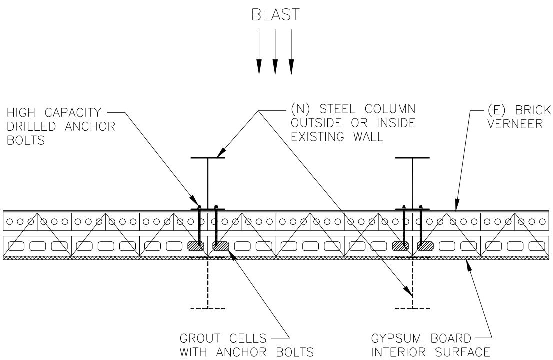

FIGURE 10.6: Masonry Wall Retrofit with Vertical Steel Posts

The most commonly used blast resistant retrofits for buildings subject to industrial explosions include attachment of vertical steel beams to the walls, placement of a exterior blast resistant wall outside the masonry wall, and bonding high strength fiber reinforced material to the wall surfaces. In all retrofits, the upgraded masonry walls perpendicular to the blast loads can also serve as shear walls. They should be analyzed for in-plane shear and bending according to the procedure outlined in Chapter 7. Connections between shear walls and diaphragms and the foundation must also be evaluated.

FIGURE 10.7: Exterior Tube Section Posts Bolted to Masonry Wall

10.7.1 Upgrade with Steel Posts

Figure 10.6 shows a cross section through a masonry wall retrofitted with vertical steel posts, which are not assumed to act compositely with the wall. This upgrade requires a minimum of available wall space compared to most other retrofits. The posts, which span between the floor and roof diaphragms, are usually placed at 4 to 7 ft (1.2 to 2.1 m) spacing depending on the capacity of the masonry wall to span between posts. They can be placed on the inside or outside of the wall. Typically posts are placed on the building exterior to avoid interior operational disruption and fixtures attached to the wall. In this case, the connections between the posts and the wall are more critical and the compression flange of the post is laterally unsupported during inward response to blast load. These posts can be notched at low moment regions or doglegged around existing conduit that typically run horizontally along the wall exterior. Galvanized steel may be considered for externally mounted posts.

Vertical post retrofits can be designed for very high blast capacities depending on the post size and spacing, although the lateral load resisting system of the building must resist the peak lateral load transferred by the upgraded walls. They also can resist blast loading effects during both inward and rebound response, as required for load bearing walls. The posts can also be positioned to support reaction forces from blast resistant windows and doors. Interior posts can be covered with light architectural panels for aesthetic reasons, but these panels must be well attached to any interior posts so that they are not thrown into the room by the sudden acceleration

FIGURE 10.8: Heavy Steel Panel on Blast Side of Retrofitted Wall

of the posts under blast loads. Exterior panels can also be covered by architectural cladding designed for conventional loads.

The maximum size of posts is often limited by the available strength of the connections of the post to the wall or the connections between the ends of the posts and the foundation and floor or roof diaphragm of the building. Through-bolts with plate washers can be used to attach posts to ungrouted CMU walls. Drilled anchor bolts that are recommended for dynamic loading can be installed into grouted CMU blocks and solid masonry walls. Placement of grout into ungrouted CMU walls requires attention to details; usually the face shells must be removed and the cells must be cleaned of any mortar to ensure placement of solid grout that acts together with the CMU block to resist pullout of anchor bolts connecting the posts to the wall. The summed tensile capacity of the anchor bolts should be greater than the ultimate load resistance of the post and there should be at least four to five bolts along the span of the connected post. The anchor bolt dynamic design capacity can be taken as 1.7 times the static allowable capacity recommended by the manufacturer, as recommended for connections in *UFC 3-340-02*. The attachments are also critical for interior posts on a load-bearing wall, since the posts must also support the wall during rebound response to blast load. The posts are usually designed for light to moderate damage because there is some concern regarding the ability of the drilled anchors on external posts to remain well attached to the wall at large post deflections.

FIGURE 10.9: Through-Bolts on Inside Surface of Retrofitted Wall

Horizontal beams can be used rather than vertical posts, but the vertical posts typically transfer their reactions directly into floor and roof diaphragms, which are part of the lateral load resisting system of the building. Horizontal beams typically transfer their lateral reaction loads into columns, which must also resist axial loads. Figure 10.7 shows exterior steel posts bolted to grouted cells of an unreinforced CMU wall. Figure 10.8 shows a heavy corrugated steel panel, which functions in a similar manner as closely spaced vertical posts, spanning vertically on the exterior side (i.e. blast loaded side) of an unreinforced, ungrouted CMU wall. Since the wall is ungrouted, through-bolts were used to connect the corrugated steel panel to the wall. Figure 10.9 shows the through-bolts and plate washers on the inside face of the wall. The vertical strap along the wall in Figure 10.9 is unrelated to the wall upgrade.

10.7.2 Upgrades with High Strength Fiber Bonded to Wall

High strength fiber strips or mats, including carbon fiber, Kevlar® (Figure 10.10), and E-glass (Figure 10.11) fibers, can be applied to the inside (i.e. non-blast loaded side) or to both sides of masonry walls to significantly increase the wall blast capacity. Parallel, very closely-spaced high-strength fibers are encased by the manufacturer in thin resin mats or strips that are bonded to the wall with the fibers oriented in the span direction. The fibers act compositely with the masonry similarly to steel reinforcement, where the tensile strength of the fibers and compression strength of the masonry form a resisting couple at the maximum moment regions. The proper application of the bonding agent and the high strength fiber mats or strips to the wall is critical and must be performed by a trained applicator.

The ultimate tension strength of the fibers per unit width is provided by the manufacturer, but typically only a fraction of the strength can be counted on for design due to debonding and/or environmental degradation factors. Also, the high

FIGURE 10.10: Kevlar® Wrap Retrofit to CMU Panel

strength fibers can not be counted on to significantly increase the compression or shear strength of the masonry. Therefore, the maximum blast resistance of a retrofit with high strength fibers is usually limited by crushing of the masonry block in the maximum moment region or shear failure of the masonry near the supports, which are both brittle failure mechanisms. Fiber tension failure, which is often initiated by debonding, is also brittle and thus this upgrade is always limited by a non-ductile response. Therefore, this type of retrofit is usually designed to resist blast load without yielding with a safety factor based on available blast test data, manufacturer's recommendations, and/or previous design experience.

An advantage for this retrofit is that it significantly reduces the potential deflection of masonry walls, which may be important for load bearing wall systems. Another advantage is that in most cases this retrofit approach does not significantly affect the aesthetics of the building, since it just changes the building surface. However, fiber attachment to the wall interior can present construction challenges and limit building operations during construction. Use of strips rather than a continuous mat can allow placement of retrofit around equipment attached to the wall as shown in Figure 10.12. Additional high strength fibers can be placed around window and door openings to resist loads transferred by blast resistant window and

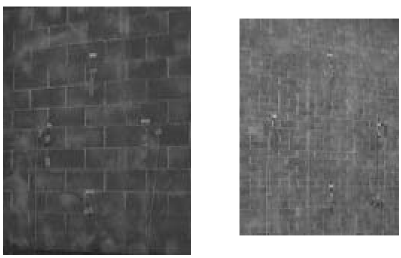

FIGURE 10.11: E-glass Retrofit to CMU and Brick Masonry Walls

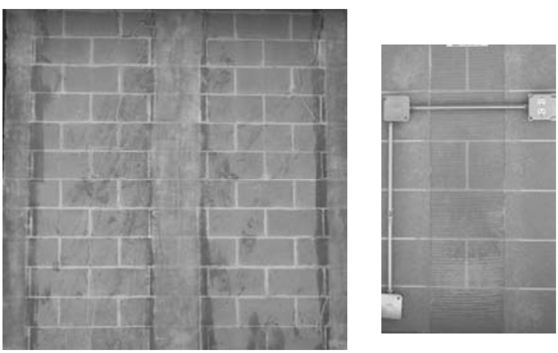

FIGURE 10.12: FRP Strips on Walls and Around Existing Interferences

door replacements. CMU walls strengthened with high strength fibers may need to be grouted so that the overall wall blast capacity is not controlled by the relatively low shear strength of ungrouted masonry. Ungrouted walls can be grouted by removing face shells at various locations, cleaning out any mortar from the cells, and pumping grout into the voids of the CMU blocks. Load bearing walls should be upgraded by attaching high strength fibers to both sides of the wall to prevent wall failure during rebound.

10.7.3 Increasing Wall Thickness with New Layer of Reinforced Concrete

Reinforced concrete panels can be upgraded by increasing the wall thickness on the exterior side with a layer of reinforced concrete that is well connected to the existing wall to create composite action between the new and existing wall sections. This upgrade can be installed by doweling into the existing concrete panel exterior and hanging a reinforcement grid parallel to the wall. A nozzle-applied shotcrete or cast-in-place concrete can then be placed to increase the overall wall thickness and flexural capacity. If shotcrete is used, the concrete surface must be prepared and existing conduit and piping should be shielded against overspray of the concrete. It is not recommended that existing conduit along the panel exterior be cast within the new wall thickness. This process is viable if the required thickness increase is only several inches and the additional wall weight does not require modification of the existing foundation. This upgrade also allows for casting concrete around existing wall penetrations.

10.8 UPGRADE WITH BLAST RESISTANT SHIELD WALL

Almost any wall system can be retrofitted by placing a blast resistant shield wall outside the existing wall. The shield wall can consist of a blast resistant precast concrete panel as shown in Figure 10.13. It can also consist of a blast resistant cast-in-place panel, or a blast resistant girt/steel cladding system as shown in Figure 10.14. Some vendors have developed prefabricated blast resistant wall systems that may be appropriate for a given upgrade depending on available test data validating the system for the given applied blast load. A third-party review of a vendor's design by an engineer familiar with blast testing and design is generally recommended.

A gap that is greater than the predicted shield wall deflection should be maintained between the shield wall and the existing building wall. This will prevent the shield wall from deflecting into the existing wall, and possibly failing it, as it responds to the blast load. The engineer should also verify that the sudden deflection of the shield wall does not decrease the void volume between the shield wall and existing wall such that there is an increased air pressure that can fail the existing wall. Small vent openings in the existing wall combined with adequate shield wall standoff from the existing wall, on the order of several feet, can be configured to prevent this potential problem. These vent openings can be covered with low-strength, lightweight

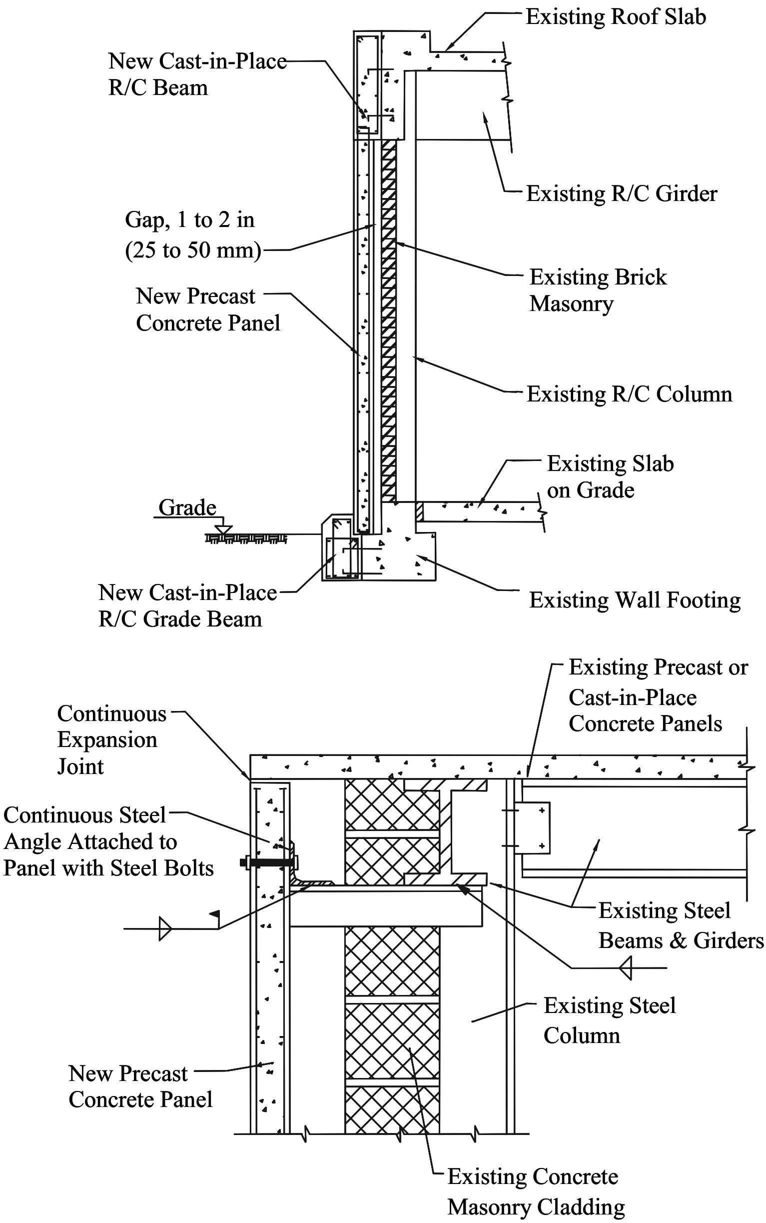

FIGURE 10.13: Wall Upgrade with Blast Resistant Precast Concrete Shield Wall