STANDARD GRADE RESILIENT CE EARTHBAG: **Rebar Anchored in Spot Footings for Moderate Risk**

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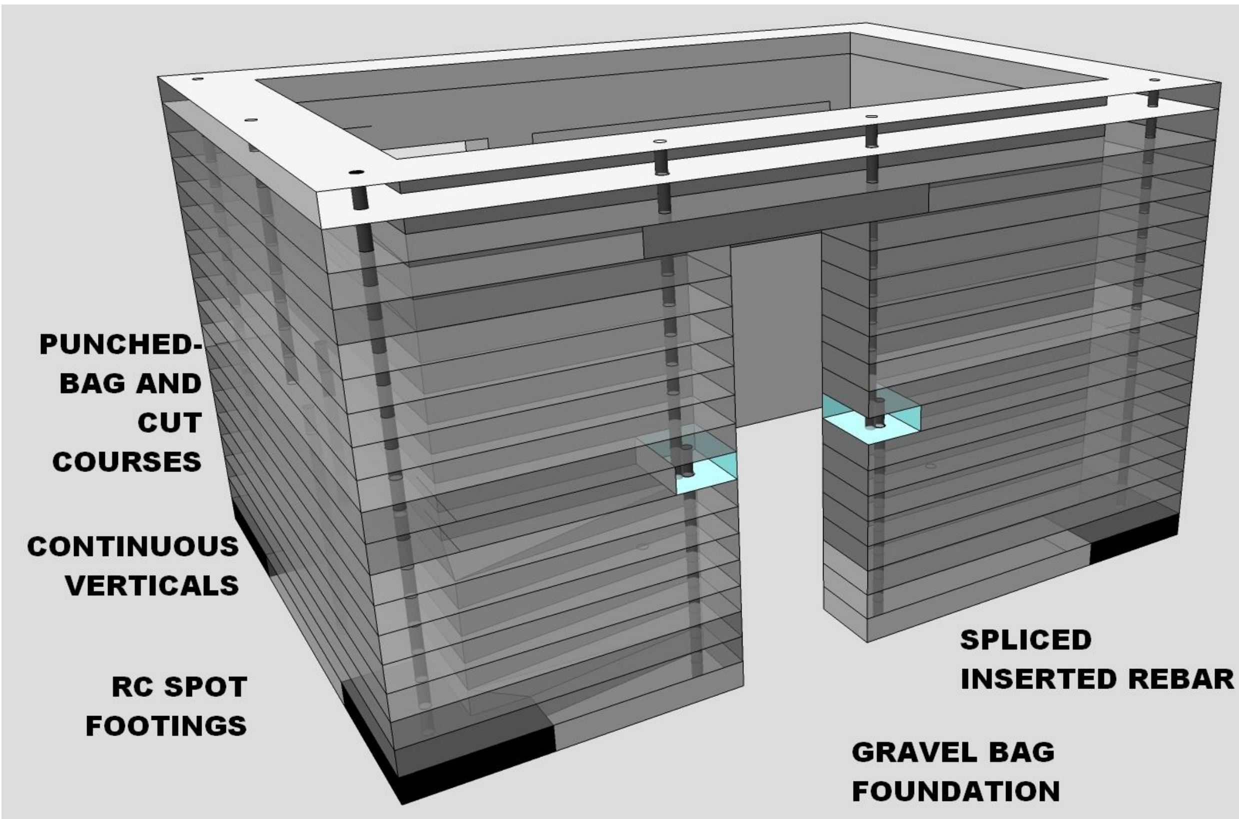

Figure 1: Strengthen corners with vertical rebar that is base-anchored in spot reinforced concrete footings. Insert spaced lap rebars at other locations on gravel bag foundations.

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INTRODUCTION

EARTHBAG VS. EARTHQUAKES

Conventional earthen buildings are well suited to areas with minimal or no seismic risk. But in places with moderate risk earthquake forces can damage or destroy buildings of earth, stone, or brick unless they are built very carefully.

Earthbag on gravel bag base walls has been used in seismic risk areas because it provides a low cost and low cement way to build walls that resist quakes better than unreinforced earthen block or rammed earth walls. Barbed wire between courses adds toughness and unconnected but easily inserted rebar provides some stiffening. Unfortunately conventional earthbag buildings have to date only survived low earthquake forces (70% or less of gravity in Nepal's 2015 quakes). Structural testing shows that they can be damaged. Quake forces can reach 170% of gravity or higher.

Earthbag buildings with conventional detailing are unlikely to collapse if barbed wire is continuous around corners and walls have well-spaced openings. But door and window frames may be broken and upper walls warped out of shape enough to require rebuilding.

Most communities want institutional buildings to *predictably* resist local quake forces.

IMPROVED REINFORCEMENT FOR MODERATE RISK

Builders love earthbag because it uses local, natural materials and because it can be built without either power tools or a lot of fussy details. It also is exciting to see immediate walls rising without pre-forming blocks or forms. The type of builder who likes to build without a complicated process also doesn't like complex planning and plans.

With new details resilient CE (contained earth) on gravel bag foundations can predictably survive in moderate risk areas **if strongly cohesive soil fill is available**. The details included in this system of reinforcement do not need extensive pre-planning. Reinforcement is either inserted into walls, or pre-anchored at corners, and lintels connect upper to lower rebar.

In areas with moderate seismic risk use these details if:

- soil fill for construction is 1,7 MPa (250 psi) compressive strength or higher
- builders are willing to take special care and use this whole system of detailing

If soil fill is weaker than 1,7 MPa (250 psi) or cannot be proven that strong, use details in *High Strength Resilient CE Earthbag* with reinforced concrete spot footings at corners (pdf online at BuildSimple.org).

Plan carefully and build thoughtfully. The details for standard grade resilient CE earthbag are for use in buildings that are:

- less than 600 m^2 (6458 s.f.) for one story or 300 m^2 (3229 s.f.) per floor with a loft or upper story
- one story or one earthen story with a light upper level
- built on firm ground (> 600 mm/ 2' from a downhill slope and not erodible or likely to subside)

Contained earth earthbag has not been fully tested, but years of small scale research have proven which reinforcement techniques are buildable and cost-effective. The improved details that follow are the best known in late 2020. Details and specifications from the guidelines in New Zealand's *Earth Buildings not Requiring Specific Engineering* (NZS 4299) for reinforced adobe should be compatible.

WHAT IS 'MODERATE' RISK?

Earthquake risk varies a lot from area to area. The sketch maps below (Figure 2) give rough estimates of risk. . Areas shown as white or light gray have lower risk levels. Builders in the US, Canada, Europe and Australia should check exact risk for their building site online.

The areas shown on the sketch maps in dark gray range from moderate risk near 0.6 g to high risk near 1.7 g. Details in this booklet can be applied to some parts of this range of risk levels.

Areas shown in black have much higher risk levels. The details in this booklet are not strong enough to ensure buildings in the high risk regions that use this standard grade resilient CE earthbag reinforcement system will be useable after strong quakes.

Build Simple Inc. uses risk levels that match the most complete existing earthen building guidelines (developed for New Zealand) to define moderate risk as:

0.6- 1.7 g (gravity) peak ground acceleration (pga)
occurring in quick 'Ss' pulses of 0.2 second that cause the most damage to low-rise buildings
likelihood of 2% probability of excedance (pe) in 50 years.

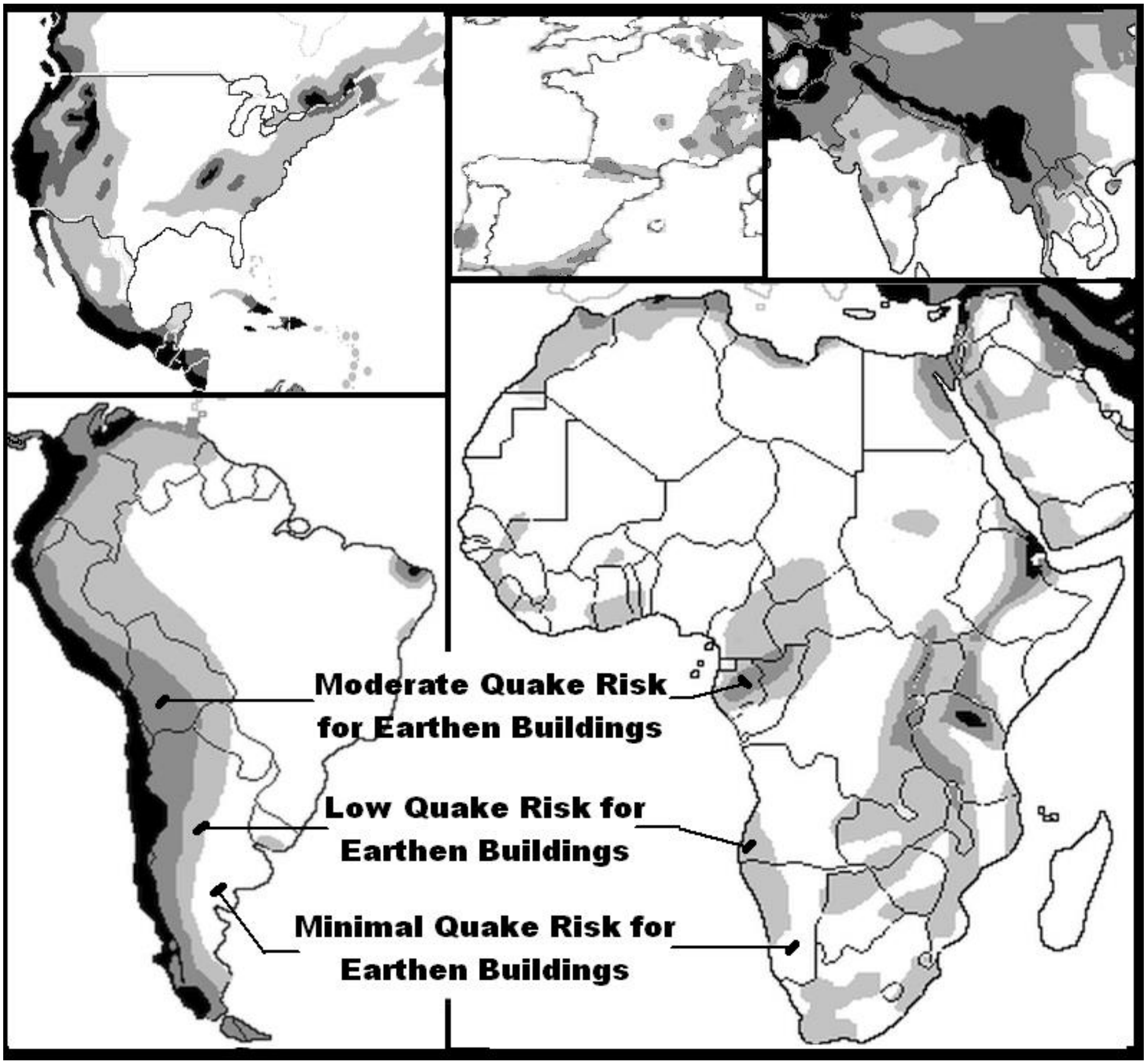


Figure 2: Approximate locations of earthquake risk relative to earthen wall strength.

Risk levels are complicated. Locations with soft soil or seasonal high groundwater have higher risk than areas with bedrock or hard stony ground. Ask an engineer or professor of engineering for advice if there are no clear guidelines enforced by local government.

Professionals in different countries talk about risk using different scales of measurement. In some areas planners use 10% in 50 year probability of excedance, as seen in the online world maps in the Global Earthquake Model (GEM)[1]. On 10% pe maps the same level as our 'low' risk is measured differently:

[1] Global Earthquake Hazard and Risk Model online at https://www.globalquakemodel.org/gem

BSI earth building risk maps[1]	2% probability in 50 years	0.6- 1.7 g pga	dark gray
GEM earthquake hazard maps	10% probability in 50 years	about 0.1- 0.3 g pga	yellow

New Zealand's code may be a helpful resource for builders in areas with seismic risk as high as 1.7 g at 2% pe. The original version of *Earth Buildings not Requiring Specific Engineering* (NZS 4299:1998) can be used for adobe block or rammed earth and the recent revision (NZS 4299:2020) for CEB (compressed earth block).

Earthbag builders may refer to New Zealand's code for details from reinforced earth walls that can be used with resilient CE. In regions from 0.6 g up to almost 1 g CE earthbag's high flexibility may result in lower requirements for steel and cement than those the New Zealand standards requires for adobe, rammed earth or CEB construction if the ductility of the earthbag material can be considered.

WHAT STRENGTH OF QUAKE CAN EARTHBAG SURVIVE?

Designers and engineers focus on trying to reduce risk, so we can't just guess. Current recommendations for level of seismic risk must be conservative. Structural testing hints that earthbag will be shown to perform well under higher earthquake forces, but at this time it is not proven. This author has structural test results soon to be published. Those who need to evaluate exact structural performance in specific tests can check the BuildSimple.org website for recent news.

Test strength results to date underestimated the potential of resilient CE earthbag because they are based on 60% scale testing of earth-plastered samples with scale-reduced rebar and 80% scale testing of unplastered samples with faulty reinforcement. Tests either allowed rebar to rotate at the base attachment or connections at the bond beam failed, so It is very likely that future testing with better full-scale reinforcement in full-scale walls with stucco finish layers will perform better.

To make test results practical earthbag can be compared to strengths seen in tests for New Zealand's code of unreinforced adobe (allowed up to 0.59 g risk) and reinforced adobe (allowed up to 1.7 g risk).

Earthbag reinforced with inserted lapped rebars has tested 2/3 as strong as unreinforced adobe. It was also about 3 times more ductile (a measurement of flexibility and the ability to survive force without a quick strength decline). US engineering code recognizes ductility as reducing the need for strength, but engineers are unwilling to use unusually high ductility factors in formulas. Ductility as high as testing has shown in earthbag with connected reinforcement does not happen

[1] https://buildsimple.org/BSI_Risk _Map

in other moderate-strength masonry materials. The unusual qualities of resilient CE mean that engineers will require more convincing to acknowledge its suitability for high seismic risk areas than for conventional stiffer materials like reinforced concrete and reinforced fired brick. So our estimates below consider less ductility than test results show.

TABLE 1: COMPARING APPROXIMATE ESTIMATED PERFORMANCE OF EARTHBAG TO ADOBE

(Adobe strengths based on published information about the development of New Zealand Standards 4299:1998)

	Tested ductility	Considered ductility	Force level deformation starts increasing	Maximum force
Resilient CE earthbag compared to unreinforced adobe allowed up to 0.59 g risk				
Overlap-reinforced CE (medium[1] fill)	2.5 x higher	2 x higher	100%	100%
Overlap-reinforced CE (strong[2] fill)	3 x higher	2 x higher	130%	130%
Connected-vertical CE (medium[1] fill)	2.5 x higher	2 x higher	113%	130%
Connected-vertical CE (strong fill)	3.5 x higher	2 x higher	143%	188%
Resilient CE earthbag compared to reinforced adobe allowed up to 1.7 g risk				
Connected-vertical CE (strong fill)	1.75 x higher	1.5 x higher	36%	47%

[1] Medium fill 1,38- 1,59 MPa (200- 230 psi)
[2] Strong fill 1,70- 2,07 MPa (250- 300 psi)

Strength before starting to deform more quickly (yield) is often used in the developed world as a minimum. This is to not only avoid any possibility of wall and roof collapse at maximum force, but also to prevent extensive rebuilding needed when sheetrock covered interior walls are damaged.

Earthbag is quite different from most masonry after experiencing maximum forces. In structural testing it begins to crack plaster after yield strength (which is easily repaired), but even after maximum strength earthbag walls remain standing and take work to disassemble. In the unlikely case of maximum earthquake forces right at a building location, well-built earthbag walls with enough bracing to resist maximum forces may be deformed enough to need some rebuilding, but will be still standing and holding up a roof.

Until further testing is completed, this author recommends that careful builders ***GET ENGINEERING ADVICE BEFORE USING STANDARD GRADE RESILIENT CE IN SEISMIC RISK LEVELS ABOVE 0.85 g***, half as high as allowed for reinforced adobe by code in New Zealand.

Although no anecdotes can prove earthbag's strength level, one from rural Nepal is reassuring. A heavy truck had a driving accident on a ridge top. The driver must have been moving fast, because the vehicle ended up on top of an earthbag residence (Figure 3) on a hillside below. The earthbag building walls were not damaged, although the roof had to be rebuilt. This house included a low-ceiling loft area with a welded tubular steel floor structure.

Figure 3 Roof but not walls of earthbag building damaged by truck accident.

More natural walls that can resist impacts from vehicles or natural disasters are needed. We hope that others will carry this research further, providing more certain understanding of the exact performance of resilient CE.

RESILIENT CE EARTHBAG REINFORCEMENT SYSTEMS

Buildings facing earthquake forces need a full system of reinforcement that matches their level of hazard. Each part of the reinforcement system must resist the same level of horizontal shaking.

Buildings often begin to fail at the single weak element that breaks or separates first. After one element fails, the rest of the building suffers increasing damage. Like a chain that is only as strong as the weakest link, buildings facing quake forces are only as strong as the weakest of their materials and connections.

This document is part of a series. Other reinforcement systems are described online at BuildSimple.org/ Resources. Reinforcement for lower seismic risk levels is defined as low-cement resilient CE and for higher seismic risk levels is defined as high strength resilient CE.

The main differences in the systems of reinforcement that can be used for earthbag are listed in Table 2. Low-cement has no rigid footings and connected verticals only at corners. Standard grade has connected verticals at corners and doorways, and spot footings only at corners. High-strength has connected verticals at all openings and continuous confining rigid strip footings.

TABLE 2: COMPARING REINFORCMENT SYSTEMS FOR RESILIENT CE

	Low-Cement	**Standard Grade**	**High-Strength**
Footings	Gravel bag	RC spot at corners	RC strip entire length
Base Wall	Detached angled pins	Covered splices	Covered splices
Corners	Open splice + fork	Continuous verticals	Continuous verticals
Intersections	Open splice + fork	Open splice	Continuous verticals
Techniques	Punched	Punched and cut	Punched and cut
Rebar	Mostly inserted	Spliced @ doorways	Continuous or spliced
Windows	Lap from bond bm	Connect verticals to bond bm	Truss upward pins to bond bm
Doorways	Connect to bond bm	Connect verticals to bond bm	Truss upward pins to bond bm
Lintels	Wood	Wood or Reinforced concrete (RC)	Wood or RC
Bond beams	Wood	RC or steel (wood with Ceiling diaphragm)	RC or steel

The reinforcement systems specify reinforcement at corners, wall intersections, and on each side of wall openings. It is not yet known how much intensive vertical rebars (at close regular spacing) will help earthbag to resist higher earthquake forces. Because base-anchored rebar is more effective at bracing designers may specify extra verticals in corner spot footings of standard grade or along entire wall panels of high strength CE.

NOTE ABOUT DIMENSIONS

To make this information accessible for builders worldwide, both metric and imperial units are used. When the measurement is an approximate one, both units are rounded even though they are not exactly equal.

MATERIALS FOR RESILIENT CE EARTHBAG

CONTAINED EARTH (CE)

The strength of the dried soil masses in earthbag's walls is critical. With minimal strength cohesive soil fill earthbag walls begin to warp under the sideways forces of earthquakes at low force levels. If walls warp sideways too far, they won't be able to keep adjacent walls perpendicular to them standing tall. Serious damage could occur.

Stronger soil fill creates stronger walls. If earthbag walls are built with 1,3 Mpa (190 psi) compressive strength soil fill the moderate-strength details in this booklet may only protect walls from 0.4- 0.8 g forces.

Built with 2,1 MPa (300 psi) soil, these details should protect walls from 1 g forces or higher.

Check the fill strength with field soil tests or better. Small samples can be dried within a day. 3 cm balls can be crushed underfoot or fist sized samples tested with simple equipment to estimate strength. See more information online at https://BuildSimple.org/Soil_Tests.

GRAVEL BAGS

Foundation walls for earthbag often use gravel in bags for moisture resistance. Short tubes or bags are filled after doubling them. Gravel fill can be settled but not compressed by tamping. Fill containers less full than for CE (contained earth earthbag) to prevent course tops from bulging upward. Because reinforcement steel does not bond with gravel, barbed wire must be wrapped around gravel courses to better resist forces from the sides.

REINFORCED CONCRETE

Resilient CE building walls have enough ductility to survive vibration on flexible wire-bound gravel bag base courses. But because these earthen walls warp instead of crack or crumble, at moderate earthquake forces base-anchored steel rebar delay wall deformation significantly. Reinforced concrete is very effective at forming a stiff anchorage and at uniting a horizontal area. When a continuous or strongly connected vertical steel rod is stiffly anchored it will not allow the wall to warp until its base either rotates upward (lifting the full weight of the wall bearing on the footing), or the steel rod bends. Longer sections of wall supported by concrete footings increases the walls resistance to damage significantly, so do not reduce sizes of spot footings.

Use clean washed sand and proportions of cement approved by experts. Use as little as possible, but don't thin it out when you use it.

CONTAINERS

SMOOTH WOVEN FABRIC is most commonly used for earthbag, woven of flat polypropylene strands about 2mm wide. This breathable material allows earthen masses inside the fabric containers to dry out gradually.

The low-friction fabric surface between courses causes CE earthbag walls to flex rather than crack. Flexible barbed wire barbs and embedded steel rebar bridge the course bed-joints, creating a composite metal and natural soil layered wall. Fabric containers may help to resist walls bulging outward from sideways forces but do not increase wall strength to resist warping from forces in line with the walls.

Use good condition fabric and protect from sun damage by plastering early- in the tropics or at high altitudes within 2 weeks. After the wall fill dries the container fabric is very important to prevent material loss if walls are damaged. If any soil masses are broken or crushed at specific stress areas, intact fabric containers hold the material in place and keep walls standing.

Smooth woven fabric is available in bags or tubes. Use tubes only in moderate to high seismic risk areas, for best integration of steel reinforcement with wall material.

MESH TUBES can be used for CE earthbag and damp fill unites through the open course containers. These monolithic 'hiperadobe' walls flex less than CE in smooth woven fabric tubes and may have higher strength against warping or bulging damage to walls. The crocheted mesh tubes (like vegetable bags) are easy to work with but may cost more than solid fabric tubes. Exact strength and ductility are not yet known. Without better research mesh tubing is not recommended for building walls in moderate to high seismic risk.

CONTAINER SIZES for tube construction are measured laid flat. 460 mm (18") wide tubes are standard for small buildings.

Wall thickness varies based on how high courses are built. Holding tubes more upright during filling and shaking fill down produces fatter courses. 460 mm (18") tubes produce 380 mm (15") thick building walls with 125 mm (5") high courses if filled to 130 mm (6") height before tamping. Filling the same size containers to 178 mm (7") height before tamping produces 150 mm (6") high courses in 370 mm (14.5") thick walls.

REINFORCEMENT

Reinforcement embedded inside earthen walls may last for generations if it is non-biodegradable. In warm climates insects may cause damage over time to important hidden structural elements, so bamboo or other natural materials are not recommended. For increased longevity, consider coating rebar in contact with soil with a rust-resistant but non-slippery paint, especially in areas with highly acid or alkaline soils.

Fiberglass or basalt rebar lack surface texturing for good bond. If the bars cannot be bent to produce critical end hooks or welded to add top bolts or cross-pieces they are not recommeded for seismic risk regions.

STEEL REBAR must be ‘deformed’ (textured) for good bond with dried soil. D10 (3/8”) rebar for angled pins allows easy bending. D12 (half-inch) diameter steel rebar is common for inserted vertical reinforcement. These weights keep their strength if bent in a 50 mm (2”) radius. If bending before inserting, always bend to 90° for ease of inserting.

With stiff base anchorage larger diameter steel can contribute higher resistance to wall strength, so D16 (5/8”) diameter rebar may be used for base-anchored long vertical reinforcements.

BARBED WIRE should be 4-point galvanized. High tensile strength wire costs less and has good strength. Low tensile strength wire is harder to work with but has longer barbs. If builders want extra resistance to forces, it is possible that the use of at least one strand of heavy low-strength barbed wire could increase resistance to warping on courses subject to higher forces (such as between the middle of windows and the course above the lintels).

STRAPPING OR TIE CORDS can be common polypropylene electrician’s pull cord or other lightweight non-biodegradable twine able to resist about 90 kg (200 lbs) pull force. But unless construction is overseen by contractors experienced in earthbag who have adequate labor to complete the project quickly, strapping should be UV resistant. Knots like a trucker’s hitch should cinch tight and not slip. Fiberglass packaging straps make a strong alternative.

OTHER MATERIALS

PLASTER MESH plays a critical role in overall wall strength. Chicken wire is often used, but with time rusts and decays in contact with alkaline cement stucco or lime plaster. Plastic geomesh or fencing mesh is costly. Build Simple recommends weak plastic bird netting or fishing net because it is not costly and the fine grid of individual strands embedded in plaster transmit forces well.

PLASTER OR STUCCO must cover the walls to protect bags from UV damage in sunlight.

Earthen walls reach full strength when fully dry but survive some dampness in humid climates if the plaster lets humidity out. Earthbag built in smooth fabric containers may resist wetting better than hiperadobe because of small air gaps between dried wall material and plaster-coated fabric. Plaster made from hydraulic lime allows earthen walls to dry out better than cement stucco which holds dampness. Consider using lime or earthen plaster on an upper interior area of all raw earthen walls finished with cement stucco in humid regions.

BASIC EARTHBAG CONSTRUCTION

For those new to earthbag construction, review the basic Earthbag Information slide shows online at BuildSimple.org. Hart's book, *Essential Earthbag Construction* has many photographs and drawings of the traditional construction techniques used in minimal seismic risk areas. Videos by Geiger are also online at the Naturalhouses youtube channel, showing generally accepted practices.

BUILDING WALLS

Soil fill must be slightly damp and tamped to consolidate. Barbed wire must be laid immediately on each course and steel rebar inserted while walls are damp (within 2- 3 days of building).

The end of tubes of contained earth should overlap the course beneath at least 230 mm (9").

Vertical integration between courses comes from the barbed wire barbs embedding in soil fill and from any embedded rebars. Vertical strapping can unite base wall courses with gravel fill, but when tied over three or more contained earth courses the strapping is likely to become loose if the soil fill shrinks slightly during the drying process.

BARBED WIRE ON CONTAINED EARTH (CE) COURSES

Lay wire immediately on damp courses and on concrete splices. Pull barbed wire taut along straight walls and wrap it continuous at all corners.

Two strands of barbed wire per course should be laid 80- 100 mm (3- 4") in from the wall edges (Figure 4) leaving 180 mm (7") available to insert vertical rebar and pins. Barbed wire should not be visible in the nooks between courses and must not block the area to insert rebar.

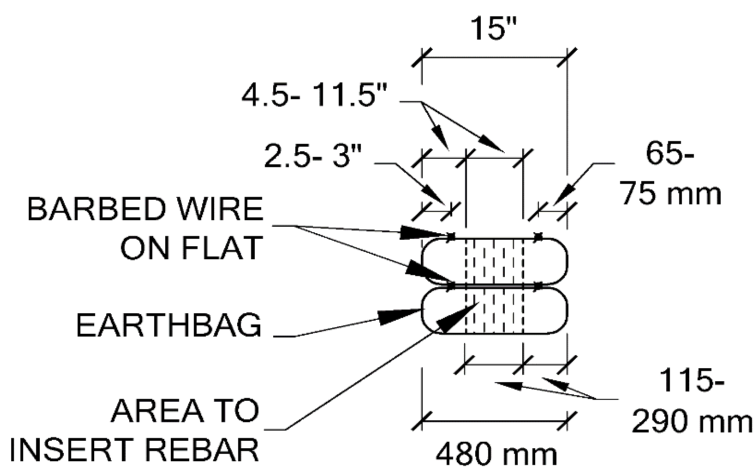


Figure 4 Barbed wire location on the flat course top near rounded course edges.

End barbed wire strands in the middle of a building side with at least a 600 mm (24") overlap (Figure 5a). At the end of a stub wall or near a wall opening, turn wire along the end and return into the wall (Figure 5b).

NOTE: NEVER END A BARBED WIRE STRAND AT A WALL CORNER OR AT THE END OF A STUB WALL.

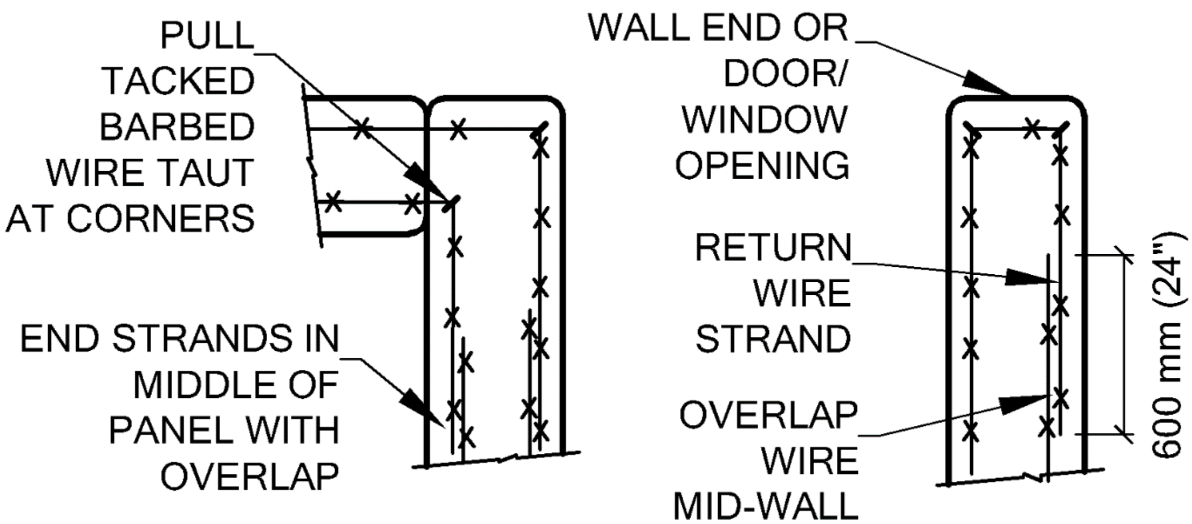


Figure 5 (left to right): a- Always run barbed wire continuous around corners and locate strand ends in middle of walls; b- Run barbed wire around wall end or opening edge and return.

Attach tie cords for plaster mesh to barbed wire letting cord hang out both sides. Space tie cords 600 mm (24”) on center vertically and horizontally.

BRACING FOR EARTHEN WALLS

Earth walls are strong against compression and can carry great weights. But without reinforcement they are dangerously weak against other types of motion including twisting. All types of rectilinear earthen walls rely on wall corners for bracing strength, and are strongest when connected to a perpendicular wall at each end. Curved walls with a radius between 1 and 3 m (3-10’) provide their own bracing. Rectilinear earthbag walls have traditionally been built with walls intersecting every 3 m (10’) or short walls called buttresses extending outward about 1 m (39”).

INTERSECTING WALLS

Wall intersections and corners need to be strongly united by bag fabric overlaps, inserted steel rebars and barbed wire.

Always alternate the direction of tubes or bags at corners to provide good running bond. At wall intersections and where walls are thickended for piers or buttresses, barbed wire must unite the separate wall segments. The strand near the exterior of the wall may receive higher stresses and should usually be continuous.

OPENINGS

Structural earthen walls must be more wall than openings.

Traditional earthbag builders know that more narrow windows are better than a few large horizontal openings for windows or doors. Maximum windows recommended are 1,2 m (4’) wide or less. Openings with included wood, brick or concrete structural frames should be widths of 1,5 m (5’) wide or less.

LINTELS

Lintels must extend further onto earthen walls than is needed on concrete block or fired brick masonry, because the weight above the lintel is concentrated under the sides resting on the wall next to the opening. Earthen walls can support lintels if the lintel extends 300 mm (12”) past the opening.

STEEL REBAR REINFORCEMENT

Rebar have traditionally been inserted in 1,5 m (5’) lengths as straight sections. Sometimes builders bend hooks on top to embed a vertical into a reinforced concrete bond beam.

INSERTING REBAR

Rebar is hammered easily into damp earthbag walls after construction. Soil fill that contains some gravel does not obstruct inserted rebar. If your fill is very stony, try a sample bag to check.

Wall material begins to firm up within hours of being tamped on a course. Inside the fabric container the interior dries out very slowly, but the surface of each course or separate unit begins to dry first. Rebar should be inserted as soon as a course is finished and tamped to be sure that the rebar embeds well with all the earthen material along its length.

Any rebar inserted into a resilient CE wall must be located near the center of the wall to avoid hitting any barbed wire. Reinforcement can be inserted at an angle running along the wall, but the rebar must be vertical relative to the thickness of the wall.

PLASTER MESH

Mesh embedded in wall plaster is an important part of the reinforcing system of resilient CE earthbag. Attach mesh firmly to the wall base and wall top. Mesh can be tied to vertical strapping on gravel bag base walls. At the wall top mesh can be run under wood bond beams or tacked to the side of the wood members. Mesh can also be pulled over exposed rebar and embedded in concrete bond beams.

The first plaster layer is usually a sticky soil with straw that adheres well to smooth woven fabric and levels the 75 mm (3”) deep spaces between courses. ‘Raw’ or unstabilized earthen plaster works well for this nook layer under a lime plaster finish coat.

For a finish coat of cement stucco, don’t waste cement stucco on the nook layer. Stucco does not stick well to the fabric. Instead, use a sticky earthen plaster stabilized with 4- 8% Portland cement or hydraulic lime. Stabilized earthen plaster will bond better with cement stucco than a ‘raw’ earthen plaster because stabilized material shrinks and swells with temperature changes similar to a cement-based stucco finish layer.

BOND BEAMS

All earthen walls must be carefully connected under a strong horizontal bond beam. Concrete bond beams are common, but wood or tubular steel have also been used. Never build any heavy earthen wall portions (like chimneys or gable walls) above the bond beam.

PART II: RESILIENT REINFORCEMENT SYSTEM

Resilient CE earthbag uses an improved reinforcement system (Figure 6) to give gravel bag courses more toughness and connect foundation weight to the top of corner verticals. Conventional earthbag walls have little resistance to sideways forces on the footing, and lack strong connections from foundation to bond beam. Resilient CE has strengthened:

- Gravel bag footings with horizontal wire binding, vertical straps, and angled pins
- Corners with small concrete splices to connect vertical rebar with diagonal forks
- Bond beams strongly attached at corners to vertical rebar with hooks or nuts

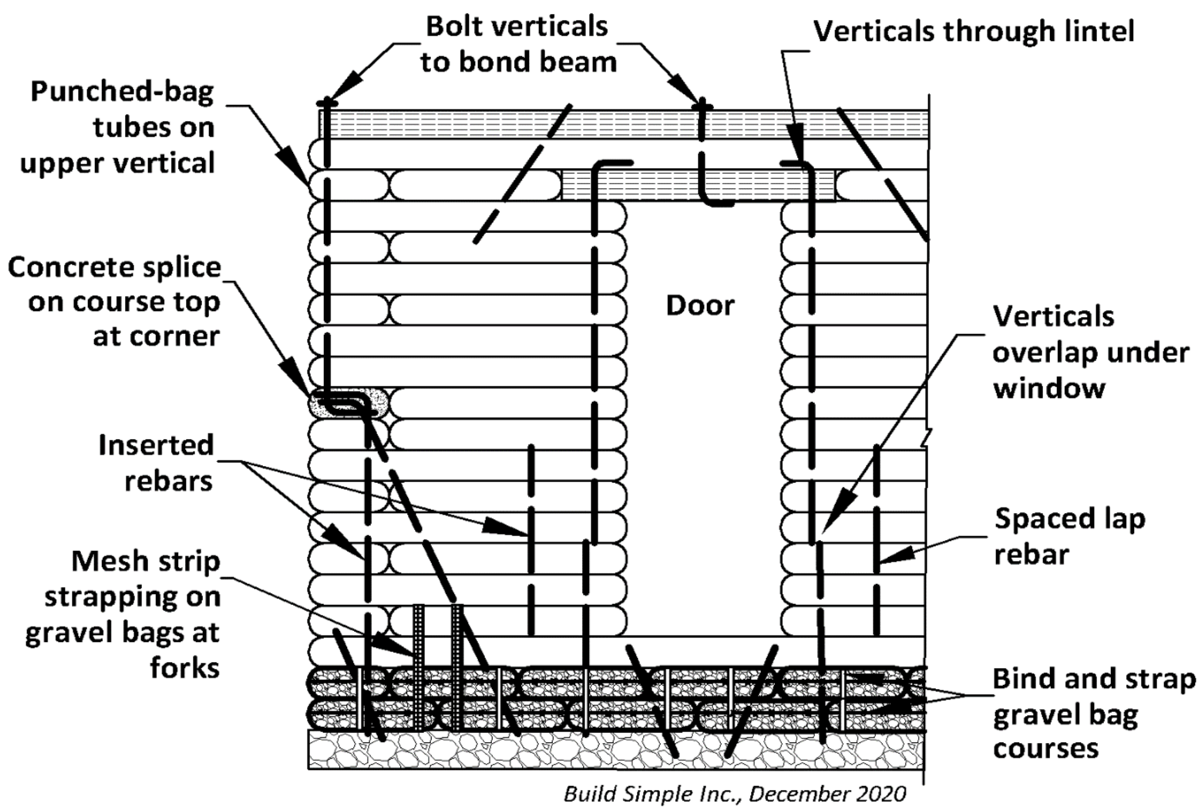


Figure 6: Improved reinforcement system for low seismic risk areas requires little Portland cement.

Additional needed wall strength also results from:

- Short lap rebars 300- 380 mm (12- 15") from aligned main verticals near wall openings
- Inserted verticals overlapped below window sill level
- Lintels attached at ends to courses below by inserted vertical rebar

Wood bond beam and lintels used with these details allow construction to use less than 1 cf (28 L) of concrete for each exterior corner.

PLANS FOR RESILIENT CE FOR LOW RISK

Earthen walls do not have to be as strong as poured concrete walls. They only need to be strong enough to keep adjacent walls connected at corners upright.

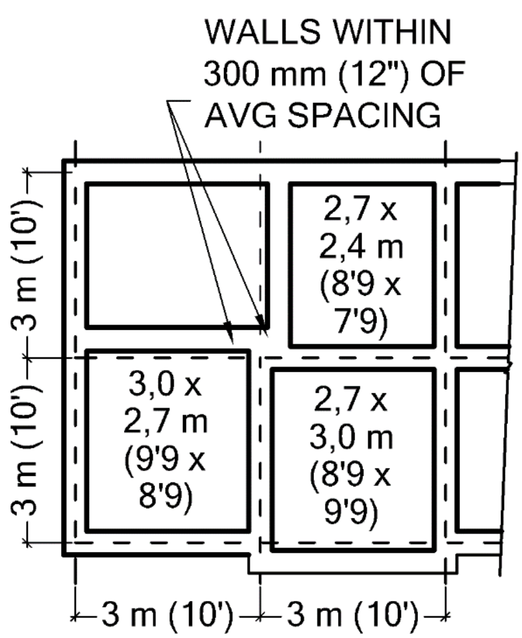
Small buildings with small room dimensions receive less stress in earthquakes than larger buildings with large rooms and heavier roof weights spanning larger distances. Square or compact rectangles suffer less in earthquakes than long buildings. Buildings with evenly spaced windows and doors suffer less than buildings with large openings on one side only.

Keep earthen buildings less than twice as long in one direction than the other. Instead of L-shaped buildings plan for two separate building. Leave more space between openings and building corners than required by standards, and use strongly built corner piers for extra stability.

ENOUGH BRACING?

Check your seismic risk level before drawing plans. It's very likely you'll need to leave 1,2- 1,3 m (39- 51") between all corners or walls and all openings. Above 0.8 g those distances will be more.

Earthquakes tend to tilt walls back and forth on their base. Bracing panels are walls attached at 90 degrees that can hold them up. Walls with doors or windows don't count- only empty walls can brace another wall. The most important task for a building designer in a seismic risk region is to check if the building has enough solid sections of walls near corners to hold all the walls up.



Corners and wall intersections closer together don't have to be as long as bracing wall panels spaced further apart. First step is to find out the average distance between walls and/ or buttresses in each major direction. Buildings do not need to be exact grids. Walls within 300 mm (12") of a bracing line act with it (Figure 7).

For each distance between bracing, specific lengths of bracing walls are needed (Figure 8a). If they are not enough, and doorways are needed near walls, extra buttresses can extend outside the building (Figure 8b). These plan examples show buttresses at their maximum of 1,2 m (4'). Doors or windows often need to be located further from wall intersections.

Figure 7 Buildings should have walls distributed at regular bracing line distances.

After checking one direction of walls for bracing, the process must be repeated. The supported wall length includes all openings. Then check if solid wall panels without openings facing the other direction are long enough. The examples in Figure 8 may need windows removed and/ or buttresses extended out the other walls also.

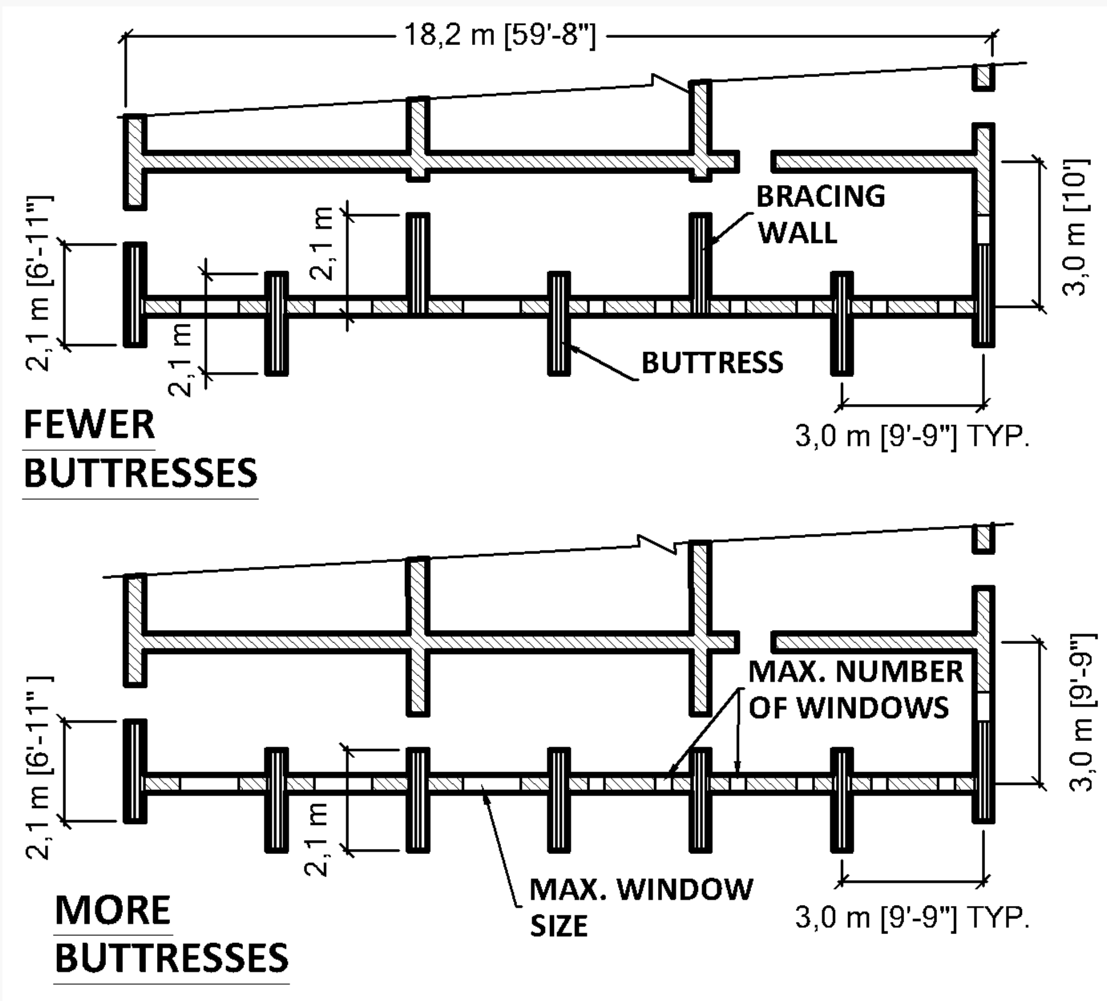


Figure 8 Examples of bracing panel sizes at 3 m (9'9") bracing line distances (above to below): a- Few buttresses and doorways distant from wall being braced; b- More buttresses and doorways closer to wall being braced.

The New Zealand Standards *Earth Buildings not Requiring Specific Engineering* (4299:1998) has a complex proces so non-engineers can check bracing while considering wall thickness, height, and the weight of a loft, upper story or roof. Standard grade resilient CE earthbag is comparable to their unreinforced adobe and performs to half the force levels of reinforced adobe. But information from NZS 4299 must be adapted because earthbag is 9% thicker than these walls and thus heavier. It is also less brittle and more flexible.

Wider distances between bracing lines will increase the length of bracing wall panels (Figure 8a, b). Earthbag builders have managed its unusual wall flexibility by using bracing distances of 3 m (9'- 9"). If designers use the 4,5 (14'- 9") spacing from the NZS or custom spacing up to 5,25 m (17'- 3") walls may need more stiffening from short piers added between bracing lines (Figure 8b).

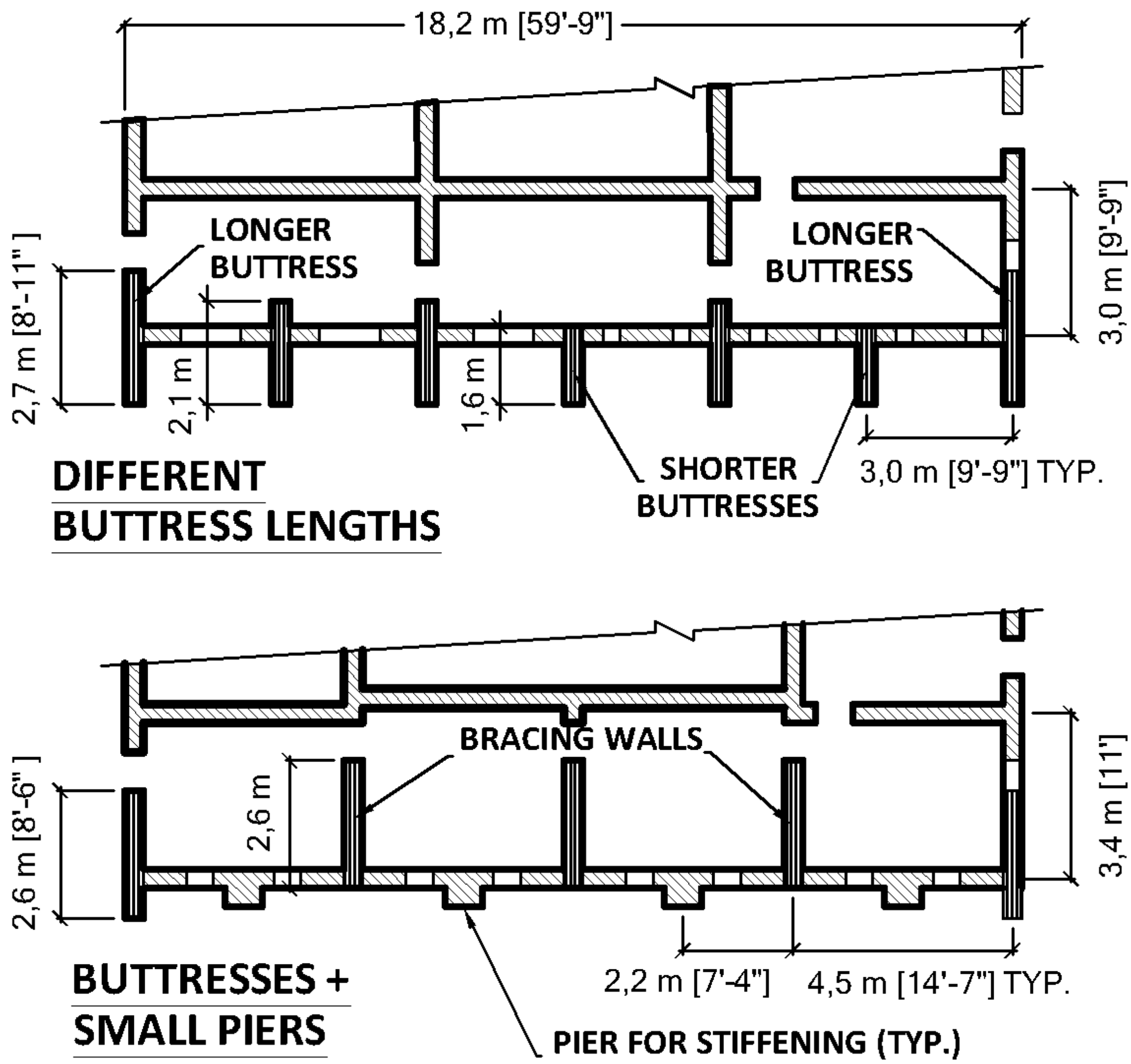


Figure 9 Examples of bracing panel sizes at different bracing line distances (above to below): a- Different buttress lengths to maximize rooms with 3 m (9'9") bracing line distances; b- Wider 4,5 m (14'- 9") bracing line distances used with stiffening piers between bracing panels.

In some buildings wider bracing lines are necessary to allow more windows per wall length.

Estimates of bracing wall panel sizes can be based on current structural testing. Use these tables for schematic planning of earthbag until newer research shows more precisely what forces resilient CE resists. The bracing wall lengths on these tables use resilient CE's maximum strength, so walls experiencing forces equal to local risk levels will undergo some damage. Wall panels 60% longer would be needed to predictably resist yield forces and prevent plaster damage.

Table 3 can be used for strong soil fill 2,1 MPa (300 psi) at seismic risk levels of 0.6 g.

TABLE 3: BRACING WALL PANEL LENGTHS FOR 0.6 G RISK WITH STRONG SOIL FILL

Approximate lengths for single story building with 2,4 m (7'- 10.5") ht. wall with light roof

Overall length of sup-ported wall	**3 m (9'- 10") Bracing Line Distance**		**4.5 m (14'- 9") Bracing Line Distance**		**5,25 m (17'-3") Bracing Line Distance**	
	Quantity of bracing panels	Min. length each bracing panel	Qty bracing panels	Min. length each bracing panel	Qty bracing panels	Min. length each bracing panel
6 m (19'- 8")	3 or 2	1,2 m (4')	- -		2	1,3 m (4'- 3")
9 m (29'- 6")	4, 3 or 2	1,2 m (4')	3 2	1,3 m (4'- 3") 1,6 m (5'- 3")		
12 m (39'- 4")	5, 4 or 3	1,2 m (4')	- -		3 2	1,3 m (4'- 3") 1,7 m (5'- 7")
15 m (49'- 3")	6, 5 or 4	1,2 m (4')	4 3	1,4 m (4'- 8") 1,7 m (5'- 7")		
16 m (52'- 6")					4 3	1,6 m (5'- 3") 1,8 (5'- 11")
18 m (59'- 0")	7, 6 or 5	1,2 m (4')	5 4	1,4 m (4'- 8") 1,6 m (5'- 3")		

Table 4 below can be used up to seismic risk levels of 0.8 g for strong soil fill of 2,1 MPa (300 psi), or for medium strength soil fill 1,5 MPa (220 psi) in seismic risk regions at or below 0.6 g.

TABLE 4: BRACING WALL PANEL LENGTHS FOR 0.8 G RISK WITH STRONG SOIL FILL

Approximate lengths for single story building with 2,4 m (7’- 10.5”) ht. wall with light roof

Overall length of supported wall	**3 m (9’- 10”) Bracing Line Distance**		**4.5 m (14’- 9”) Bracing Line Distance**		**5,25 m (17’-3”) Bracing Line Distance**	
	Qty bracing panels	Min. length each bracing panel	Qty bracing panels	Min. length each bracing panel	Qty bracing panels	Min. Length each Bracing Panel
6 m (19’- 8”)	3 or 2	1,2 m (4’)	-		2	1,35 m (4’- 6”)
			-			
9 m (29’- 6”)	4 or 3	1,2 m (4’)	3	1,35 m (4’- 6”)		
			2	1,8 m (5’- 11”)		
12 m (39’- 4”)	5 or 4	1,2 m (4’)	-		3	1,65 m (5’- 5”)
			-		2	2,4 m (7’- 11”)
15 m (49’- 3”)	6 or 5	1,2 m (4’)	4	1,5 m (4’- 11”)		
	4	1,35 m (4’- 6”)	3	1,95 m (6’- 5”)		
16 m (52’- 6”)					4	1,65 m (5’- 5”)
					3	2,25 (7’- 5”)
18 m (59’- 0”)	7 or 6	1,2 m (4’)	5	1,5 m (4’- 11”)		
	5	1,35 m (4’- 6”)	4	1,8 m (5’- 11”)		

If an engineer approves, use Table 5 for strong soil strength fill in seismic risk regions up to 1 g. The same bracing wall lengths can be used for medium soil fill walls up to 0.8 g seismic risk levels.

TABLE 5: BRACING WALL PANEL LENGTHS FOR 1 G RISK WITH STRONG SOIL FILL

Approximate lengths for single story building with 2,4 m (7'- 10.5") ht. wall with light roof

Overall length of sup-ported wall	3 m (9'- 10") Bracing Line Distance		4.5 m (14'- 9") Bracing Line Distance		5,25 m (17'-3") Bracing Line Distance	
	Qty bracing panels	Min. length each bracing panel	Qty bracing panels	Min. length each bracing panel	Qty bracing panels	Min. Length each Bracing Panel
6 m (19'- 8")	3	1,2 m (4')	-		2	1,65 m (5'- 5")
	2	1,35 m (4'- 6")	-			
9 m (29'- 6")	4	1,2 m (4')	3	1,5 m (4'- 11")		
	3	1,35 m (4'- 6")	2	2,25 m (7'- 5")		
	2	1,8 m (5'- 11")				
12 m (39'- 4")	5	1,2 m (4')	-		3	2,1 m (6'- 11")
	4	1,35 m (4'- 6")	-		2	3 m (9'- 10")
	3	1,65 m (5'- 5")				
15 m (49'- 3")	6	1,2 m (4')	4	1,95 m (6'- 5")		
	5	1,35 m (4'- 6")	3	2,4 m (7'- 11")		
	4	1,65 m (5'- 5")				
16 m (52'- 6")					4	2,1 m (6'- 11")
					3	2,7 (8'- 11")
18 m (59'- 0")	7	1,2 m (4')	5	1,8 m (5'- 11")		
	6	1,35 m (4'- 6")	4	2,25 m (7'- 5")		
	5	1,5 m (4'- 11")				

For buttresses of different lengths on the same wall, use the recommended length as the average. Shorten some buttresses by less than a third of their length and then lengthen the same number of buttresses by the same amount (Figure 8a).

The process to check for bracing panels is fussy, but builders who are careful with door and window placement will create buildings that are available when needed after local disasters.

Careful builders should also use 35% longer bracing panels for interior walls at 3 m (10’) bracing line spacing or 42% longer at 4,5 m (15’) spacing. If builders want to use taller walls, bracing panel lengths must also be increased. For 2,7 m (8’- 11”) height walls bracing panel lengths must be 12% longer, for 3 m (9’- 10”) height they must be 25% longer.

Resilient CE may be usable in seismic risk regions above 1 g. Look for more recent publications on earthbag structural performance, or seek engineering advice. Details in *High Strength Resilient CE Earthbag* may be more appropriate than these standard grade construction techniques.

Engineers can help to fine-tune building detail and plan choices for specific sites. The New Zealand standard allows buildings that are well braced in general to use 30% less bracing panels in one of the bracing lines, and have a more complex system that allows for interpolating other bracing line distances. Specific buildings for risk levels near 1 g may need to evaluated more carefully by using their full evaluation process.

DISTANCES BETWEEN OPENINGS

Reinforcement is important both next to wall openings and in wall intersections. But if earthen walls are over-reinforced, the embedded steel may reduce wall strength by concentrating forces that are too strong for the adjacent earthen wall materials. These space guidelines will prevent crowding vertical rebar reinforcement closer than 460 mm (18” apart).

TABLE 6: MINIMUM DISTANCES BETWEEN WALL OPENINGS

600 mm (24")	between a wall intersection and center of a buttress
760 mm (30")	between two wall openings
1 m (39”)	between a wall opening and the outside edge of a building corner
1,2 m (48")	between two openings with a wall/ buttress between

SPOT RC FOOTINGS FOR MODERATE RISK

Engineers usually assume that buildings in seismic risk areas need a heavy reinforced concrete (RC) foundation to stiffen walls as well as preserve the building from potential subsoil cracking or material loss under the footing. Earthen buildings with 380 mm (15") thick walls require a lot of cement to create 480 mm (19") wide footings. Resilient CE earthbag is more flexible than ordinary masonry or earthen walls and does not require stiff foundations for good strength.

Spot footings at corners can be connected to strong mesh confining mid-wall gravel bags to give the entire foundation wall more resistance against deformation from forces perpendicular to the wall and from subsoil movement. Leave undisturbed subsoil in place next to the inner edge of all footings so that the gravel bags can be firmly confined against the edge of the trench.

Buildings on soft or erodable subsoil may need stronger footings using more cement, such as a confining reinforced concrete strip surrounding gravel bags (see *High Strength Resilient CE Earthbag* online at the BuildSimple.org resources page).

SPOT FOOTINGS

Footings attached to vertical rebar must be held down by heavy wall weight. Align the edge of spot footings at corners with the exterior surface of earthbag walls so the footing is under the maximum length of walls. Spot footings should have a minimum dimension of 900 mm (3') unless otherwise recommended by an engineer.

All reinforced concrete footings need horizontal embedded steel continuous along the edges. Standard details for reinforcement of masonry footings can apply. Base-anchored vertical rebar must have good hook lengths. Use additional vertical rebars for a foundation pin at each end of the reinforced concrete.

CONNECT SPOT FOOTINGS TO LOW-CEMENT FOUNDATIONS

Use 150 mm (6") wide strips of plastic emergency fence or geomesh on the external edge of all gravel bag footings. Run them into the spot footings, connect the mesh and embed in the concrete (Figure 9).

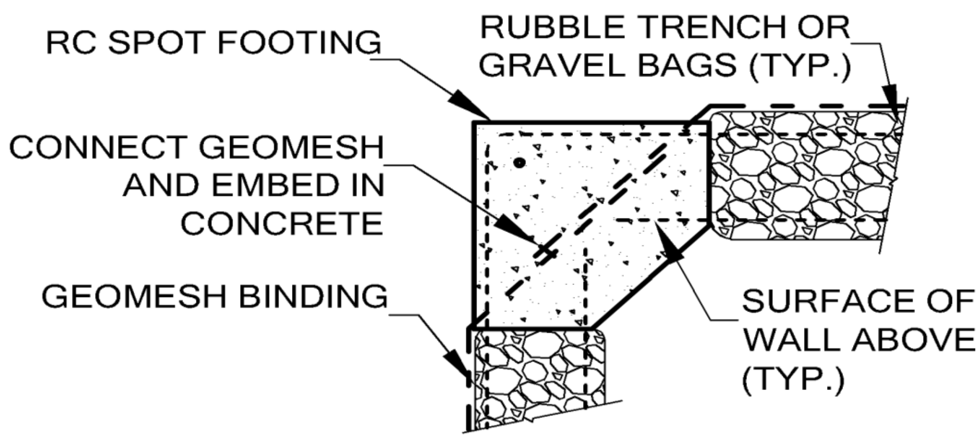


Figure 9 Geomesh embedded in spot footings at corners can confine adjacent gravel bag footings.

A rubble trench between RC spot footings can have the rubble wrapped with a strong mesh.

Locate Reinforcement for Type of Corner Construction

Vertical rebar must be near an interior corner for continuous rebar and near an exterior corner for spliced rebar construction. The simplest corner reinforcement uses continuous verticals that are located near inside edges of building wall corners.

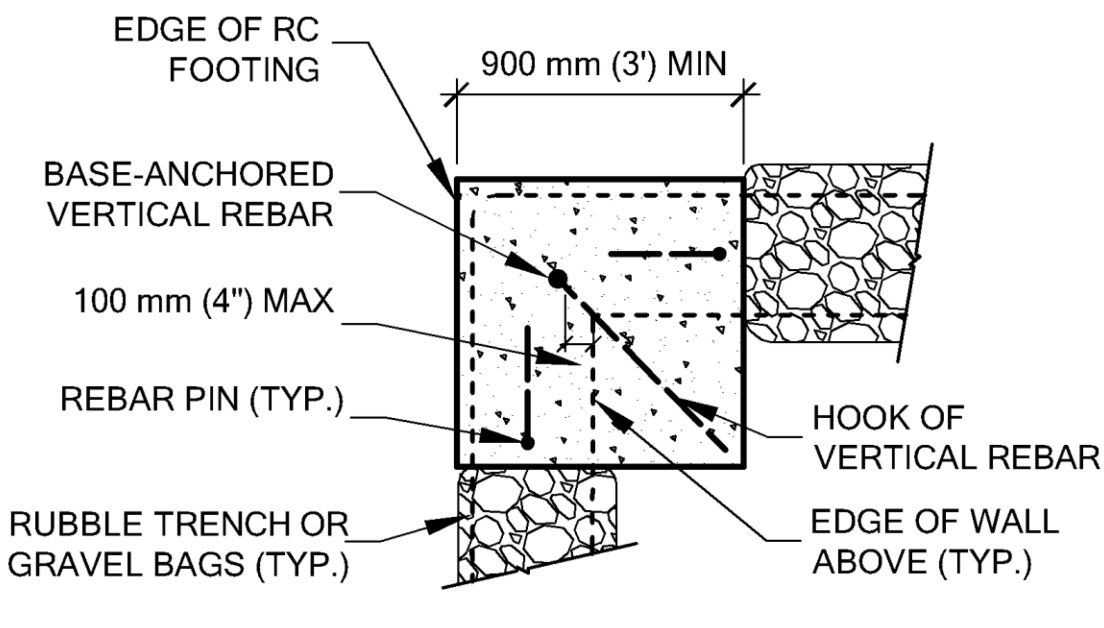


Figure 10 Spot footing to anchor long vertical rebar extending to the bond beam.

The standard open splice is easiest to build. An alternate covered splice disturbs container continuity in walls a little less, so read the section Splices to Connect Rebars on page 37 before building footings.

For an open splice, locate the lower rebar 5” from one corner and 10” from the other (Figure 11).

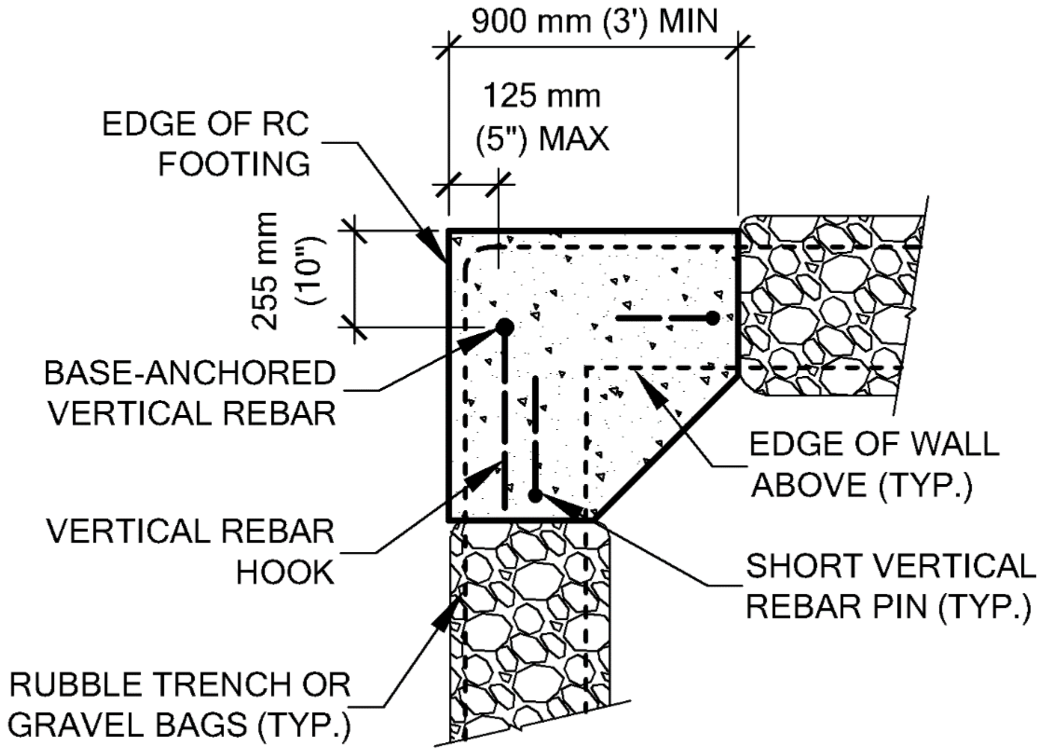


Figure 11 Spot footing to anchor short vertical rebar that will use an open splice.

To use a covered splice, locate the lower rebar at the outer corner of the wall. A 255 mm (10”) square area on the course of the splice will be filled with sand and later emptied and replaced by concrete to make the splice (Figure 12).

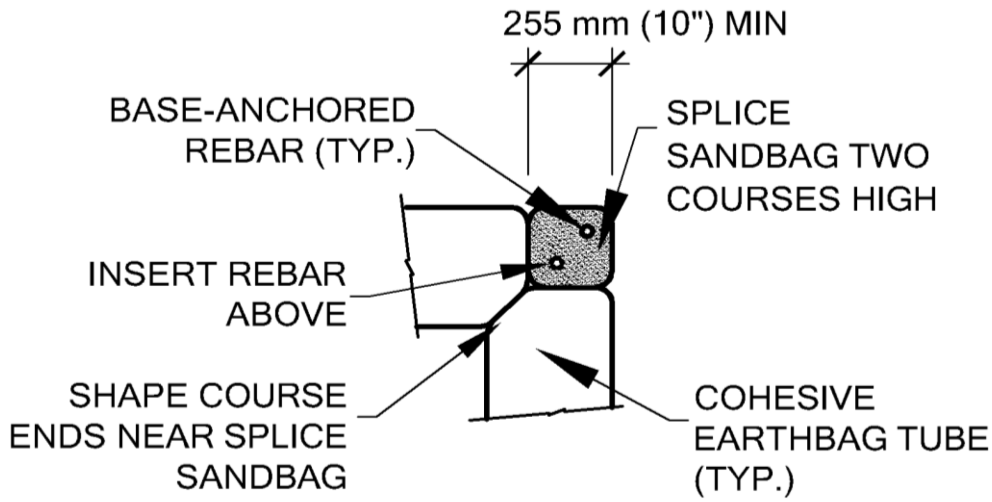


Figure 12 Covered splice sandbag location at mid-story height of external wall corners.

For a covered splice locate the lower rebar 125 mm (5”) from the face of each side of the wall corner (Figure 12).

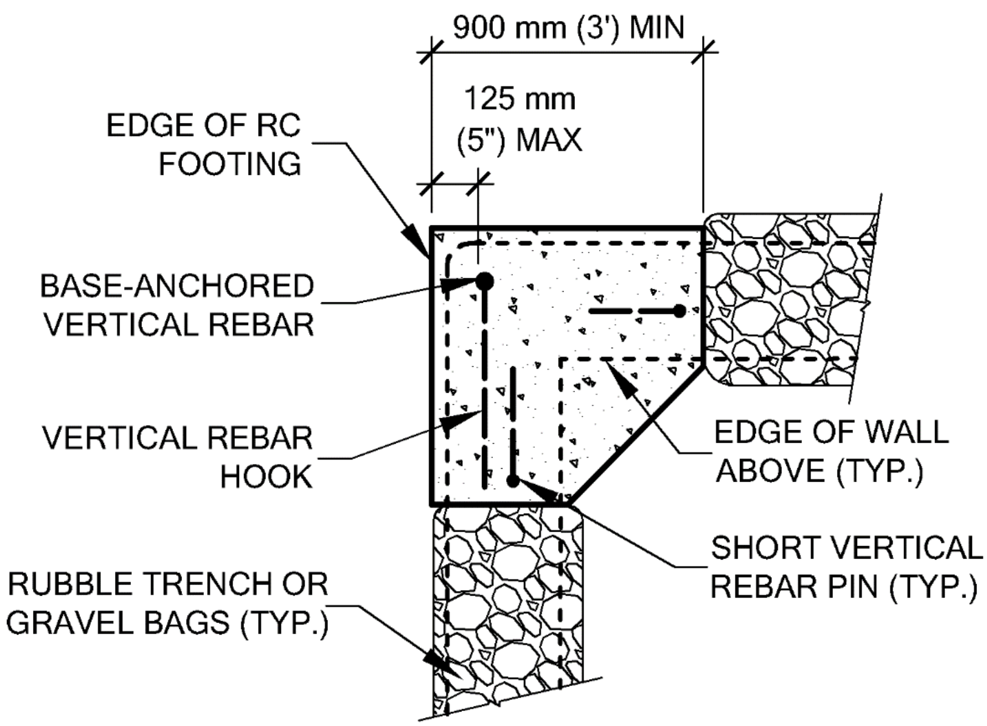


Figure 13 Spot footing to anchor short vertical rebar that will use a covered splice.

GRAVEL BAG FOUNDATIONS

Gravel bags provide well-drained base layer. When doubled and not over-filled, they have good resistance to compression and friction between courses. But gravel bags do not bond to inserted rebar so have little vertical connection.

Use vertical strapping on every bag between spot footings. Decay-resistant tie cord or strips of strong geomesh or plastic fencing mesh can be used as vertical strapping. Before laying gravel bags, place ties under each bag. Start under the first gravel bag course and attach the strapping to the barbed wire on top of the second earthen fill course..

BINDING GRAVEL BAG COURSES

Separate gravel bags may not have enough friction to resist sideways force against the center of a wall during strong quake motion. where gravel bag courses are used between spot footings. Mesh confining the sides of bag footings provide better toughness. If a building uses more than one gravel bag course before beginning contained earth courses, increase its toughness also by binding the gravel bag courses horizontally (Figure 13a).

Use a small nail inserted between the twisted wire of each strand and lever it to pull them taut. Bend the nail and wrap it and the two wires with galvanized tie wire (Figure 13b).

Figure 14 (left to right) Binding gravel bag courses: a- Wrap straight lengths; b- Attach securely.

To bind, wrap barbed wire along straight lengths of gravel bag wall (Figure 14a) where bags are laid continuous. Any buttress or stub wall that is not continuous on the course cannot be bound. On the next course that element will have bags laid continuous in the other direction (Figure 14b) and can be bound.

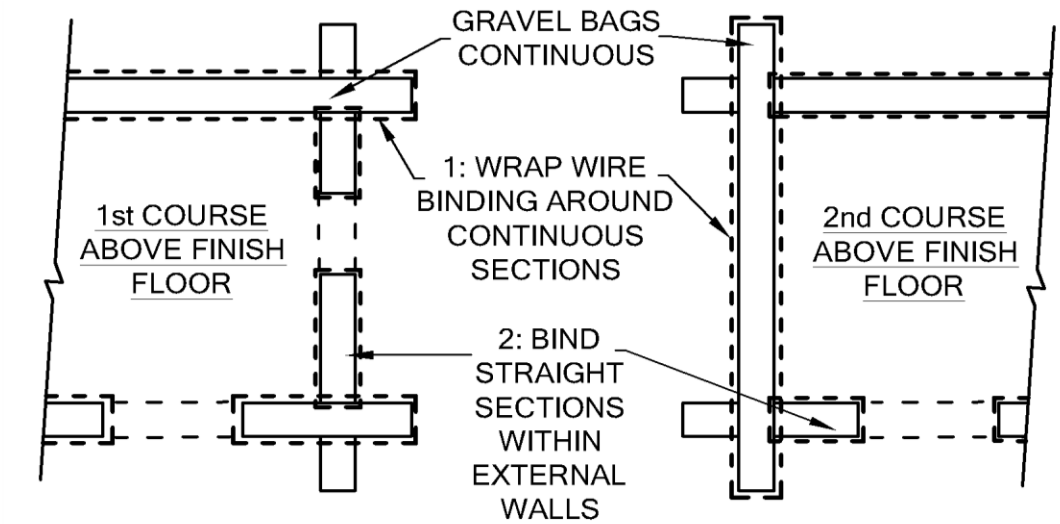


Figure 15 (right to left): a- Bind around gravel bag courses; b- Pull taut and attach wire at overlap with a nail through both strands, then hold it in place by wire wrapped around the strands.

Where walls have complex shapes, start a strand looping around a gravel bag at a recessed corner (Figure 15). Let wires pass one outer corner before the strand ends. Add an extra anchor bag overlapping the corner bags where needed to hold the barbed wire strand.

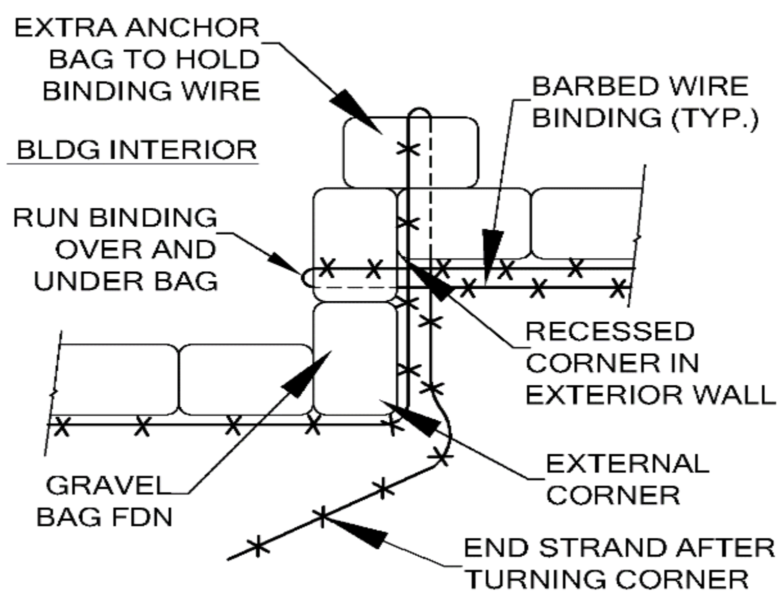


Figure 16 Start barbed wire at recessed corners by wrapping strands around a perpendicular bag.

BUILDING RESILIENT CE WALLS

Keep soil fill material just damp enough that a small handfull squeezed into a ball will split in several pieces when dropped from 1,5 m (5') high onto a hard surface. In rainy regions, cover the soil pile when not in use. Fill that is too damp may become too sticky to shovel easily. It also can be impossible to tamp until the course has dried, slowing work.

Special techniques are used in standard grade resilient CE to improve embedment of barbed wire and rebars in dried soil fill. Bags can be slid over rebar (Figure 17a) or cut (Figure 17b) to fit around base-anchored rebar reinforcement and barbs can be pinned.

Straighten barbed wire before placing and locate carefully. Make a sharp bend at a corner and hold it in place with an electrician's staple (Figure 17c). This will pin wire taut along the wall and give the corner some added strength. Place the staple on a barb at the bend in the barbed wire.

Figure 17 Techniques to embed steel (left to right): a- Punch bags onto anchored rebar; b- Cut tubes to form around rebar; c- Tack wire corners taut with an electrician's staple.

REBAR EMBEDDED IN WALL MATERIAL

The bond between dried strong soil fill and embedded reinforcement is what gives resilient CE the ability to resist earthquakes.

Angled Wall Pins

Before inserting these short rebar sections for gravel bag foundations, build two courses of contained earth above the gravel courses.

To prevent conflict between angled base wall pins and future vertical or fork rebars, mark on the top gravel course the location where vertical rebars will be inserted above at 150 mm (6”) outside of each opening. Also mark the bottom end of the corner forks at 1 m (40”) from each corner.

Insert straight rebar pins through the first two contained earth courses into and through all gravel bag courses (Figure 8). Near corners insert angled pins down toward the center of the building to help resist localized uplift forces. Use a 20° or steeper angle.

Insert angled rebars at least 100 mm (4”) apart on top of the course. Where 90 degree hooks are needed, aim them across the course top.

Angled pins can also unite piers or buttresse to building walls. If diagonals are not spliced to verticals at corners or buttresses, insert a pin every 5 courses downward from the end of the buttress or exterior of the pier toward the wall.

Angled pins are also needed as stiffening for the wall top above lintels when inserted downward from the bond beam.

Use a short 75- 100 mm (3- 4") hook on angled pins inserted through a wood bond beam or lintel. Use a longer 255 mm (10") hook on pins to be embedded in a reinforced concrete bond beam or lintel.

Base-Anchored Rebar Can be Embedded

Pairs of external pinning rebar were engineer’s first suggestions to reinforce earthbag walls, but research proves that deformed steel rebar embedded inside strong dried soil fill material improves strength much more. Techniques to base-anchor rebar but still embed them in walls use small holes or small cuts to fabric course containers. These two techniques of punched-bag or cut-bag tubes are used on vertical rebars at specific locations. Standard grade uses punched bag at corners and punched alternating with cut-bag above lintels.

Either use two separate tubes for each wall panel, or use the cut-bag technique for the other end of a single tube.

Cut-bag technique disrupts the container fabric a little when used on vertical rebar in straight wall sections. Structural testing showed that with damp fill the cut to the bag did not reduce wall strength. Cuts alternating with punched bag reduce interruption to continuous tube lengths from head joints at tube ends.

PUNCHED-BAG CONSTRUCTION

Punched bags can be placed onto rebar in many wall locations. They are easiest to do near the beginning of a tube with a small amount of fill. Locate the rebar close to either the inside or outside strand of barbed wire. They can also be used in the middle of a straight wall but will require the use of more separate tubes and will provide some disruption of the wall continuity.

Punch tubes onto a vertical at least 150 mm (6") away from the bottom of a new tube length. Alternate sides so that there is a good overlap either side of the vertical rebar.

For neat construction pre-measure and make a small cut near the stapled or sewn end of a tube. Remember the distance will include the curving bag side. For a 125 mm (5") high course measure 165 mm (6.5") and the hole will end up 125 mm (5") from the wall surface. For a 150 mm (6") high course measure 229 mm (9").

A small piece of duct tape (Figure 18a) over the bottom hole when soils have low cohesion can prevent any fill loss before placement. Place tape on clean bags before filling.

Pre-fill the end of a tube about 255- 300 mm (10-12") deep. Shake the tube and compress the fill. Place a finger in the hole on the bottom of the course, line up the hole with the rebar (Figure 18b) and slide the rebar through the bottom and then the top hole. The tube end will have loose fill when it has been slid down over the rebar. Reach inside the bag and re-firm or tamp the soil with a fist or 100 x 100 mm (4 x 4) wood piece to produce a firmly packed tube end. Continue to fill the tube and tamp after adjacent tubes are in place (Figure 18c).

Figure 18 Punched-bag technique (left to right): a- Prepared hole near tube end; b- Slide a partly-filled tube end down over a rebar; c- Filled and tamped punched-bag with no fabric gapping.

CUT-BAG CONSTRUCTION

Cut-bag tested as strong as punched-bag construction even when cuts extending around half the container perimeter. If cuts must be placed in an exposed end or side of a wall an extra builder is helpful during construction to hold a board against the cut and prevent a little soil loss.

Pre-cutting and taping at the cut locations may result in shorter and neater cuts. Fill the tube end next to the rebar but let it hang slightly over the edge of the wall on a metal 'slider' sheet. When the cut course is full past the cut location (Figure 19a), slide the tube on the metal into place with the fill surrounding the rebar (Figure 19b). Pull the metal out and settle the fabric on the barbed wire below after the course is in place (Figure 19c).

Like any resilient CE earthbag, cut-bag construction must be built with fill damp enough to solidify. Always build the cut tube first, then place the adjacent tube next to it before tamping the course. The vertical rebar aligned with the interior strand of rebar can keep barbed wire pulled straight and taut at corners.

Figure 19 Cut-bag technique (left to right): a- Cut the tube next to the rebar; b- Slide the cut tube into position to surround the rebar; c- Running barbed wire past rebar.

WALL INTERSECTIONS

Always alternate the direction of tubes or bags at corners to provide good running bond.

Use aligned or connected vertical rebar up the center of each wall intersection to strongly unite the separate walls. At wall intersections and where walls are thickended for piers or buttresses, barbed wire must also unite the separate wall elements. The strand near the exterior of the wall may receive higher stresses and should usually be continuous.

Intersecting wall wire should run continuous across the adjacent wall (Figure 20a). Buttress or stub wall wires can form a loop (Figure 20b). Tack barbed wire over the main wall wires to secure both strands. If possible, insert the tack directly over a barb. If buttresses or stub walls are opposite interior walls, run wire continuous from the interior wall to the end of the buttress.

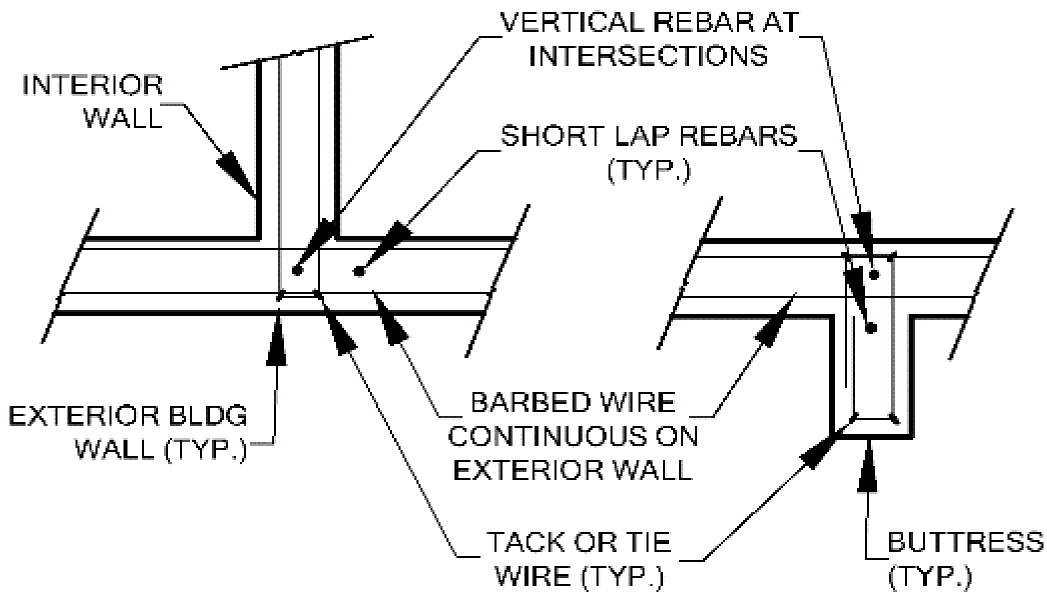


Figure 20 Barbed wire with both strands of barbed wire continuous along walls (right to left): a- At wall intersections run wire across adjacent wall, b- At buttress run wire across wall and return.

THICKENED WALLS

Thickened wall areas can help stiffen highly flexible CE against any tendency to flex or bulge outward.

PIERS

Because piers do not brace the walls that they are built on against uplift, limit pier height to 1,8 m (6’) or lower to reduce weight at the wall tops. To stiffen walls with large bracing line distances, build piers just over half of the wall height.

A pier is easy to build when it adds one extra wall thickness, and its length is a multiple of the wall thickness. Run wall tubes continuous next to the pier every other course (Figure 21a, b). Run barbed wire continuous along the wall. Use a loop to connect the pier course to the wall (Figure 22) and if possible weave this loop up onto the course above. (Note: weaving barbed wire between courses causes tangles at corners or wall ends that interfere with connection between courses, but can be done in midwall locations).

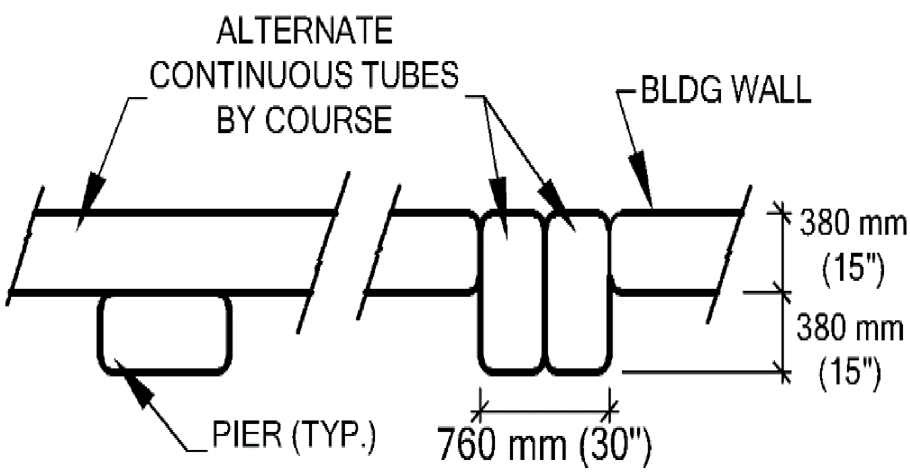


Figure 21 Piers integrated to the wall (left to right): a- Continuous tube lengths along the wall; b- Every other course interrupt the wall to run tubes across the pier and the wall.

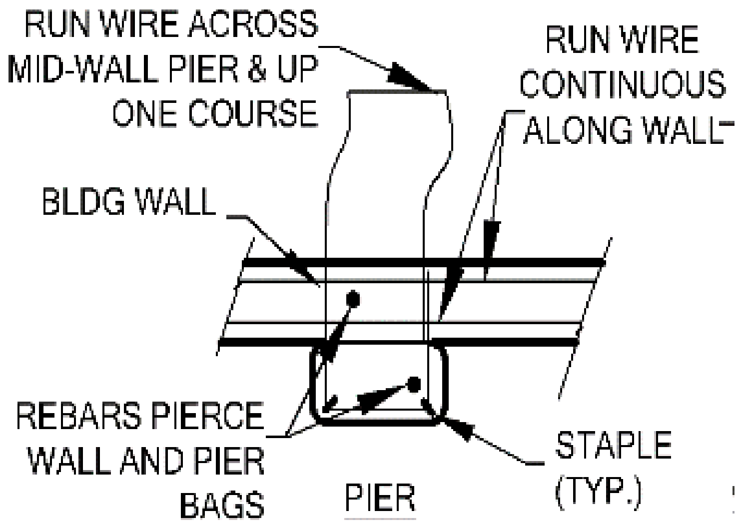


Figure 22 Barbed wire on piers should use a loop of wire woven to the next course.

Straight lengths of short angled pins can also be inserted at angles to unite walls to piers to adjacent walls.

EXTENDING WALLS AND ADDING STUBS

BUTTRESSES

Include these short wall portions under the bond beam. Because the ends of stub walls can increase damage from earthquake vibrations, don't build buttresses extending more than 1,2 m (4') long from walls.

Build buttresses the same width as walls, laying alternate courses continuous to the end of the buttress (Figure 24a, b). If buttresses or stub walls are opposite interior walls, run wire continuous from the interior wall to the end of the buttress. At a corner, run barbed wire continuous from the building walls into and around the end of the buttress (Figure 24c) in both directions. A mid-wall buttress (Figure 23a) should have the wire laid similar to a mid-wall pier (Figure 22b).

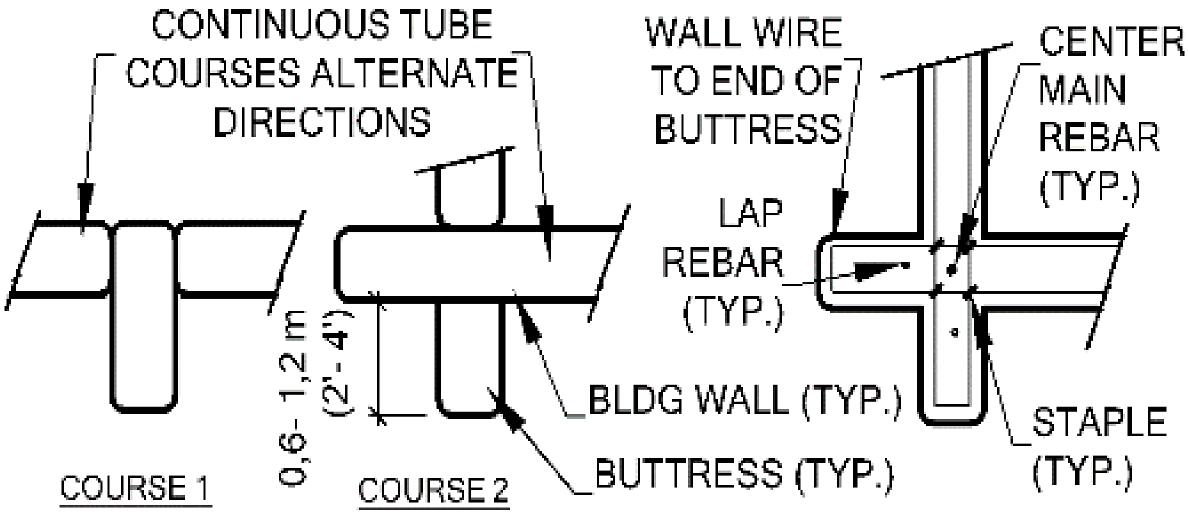


Figure 23: Continuous tubes and barbed wire unite walls to piers (left to right): a- Mid-wall buttress; b- Corner buttress tube layout; c- Corner buttress barbed wire and rebar.

BASE-ANCHORED CORNERS FOR MODERATE RISK

Rectangular buildings need corners with extra strength. External corners with connected vertical steel can reduce damage to the entire wall length of an earthbag building. Strong spot footings that hold embedded vertical rebar stiffly in place greatly increase resilient CE wall strength.

CONNECTING REBAR

Horizontal forces on walls result in strong upward forces pulling the bond beam off of any vertical steel. Holding the bond beam down on the rebar is critical for best wall strength. Various expensive or cheap types of mechanical couplers have failed repeatedly in earthbag structural tests. Have the correct end on any steel rebar to be used in earthen walls.

For buildings with wood bond beams and lintels, all major verticals at corners and wall intersections, and the long rebars at lintels should have 7" (178 mm) or longer threaded rod pre-welded on the end unless a welder can work on the top of the wall to add a cross-piece after the rebar is inserted.

Smaller vertical lap bars in wood bond beams may only need a short hook of 75- 100 mm (3- 4”). Reinforcing pins inserted at an angle of 20° or more in buildings for low seismic risk may not need hooks bent on top. For all rebars to be embedded in reinforced concrete bond beams or lintels, use long hooks. Reinforcing steel embedded in concrete should always have 25 mm (one inch) of cover or more.

SPLICES TO CONNECT REBARS

Separate rebar lengths spliced together with a concrete plug act structurally very similar to continuous rebar. Although a splice interrupts the running bond and continuity of fabric at the corners for a course, the barbed wire continues through the splice and both vertical rebars bridge it. The benefit from connecting steel is much greater than the loss of longer wall masses on a single course.

Builders may choose to use splices in some locations to reduce the need for punching tube courses. Plan ahead because no rebar inserted from above will be able to pass through a splice.

Vertical wall rebars should be located at least 125 mm (5") from a wall edge to allow enough cover depth for good soil embedment.

OPEN SPLICES

An open splice has concrete poured into a space on top of a course. Vertical and/ or diagonal rebars inserted from the same course (Figure 24a,b) are connected.

Build tubes at the splice layer to within 180 mm (7”) of the corner in one direction, and 300 mm (12”) in the other. Leave an exposed gap large enough to include the hooks of the rebars (Figure 24c). Turn hooks on diagonals across the course. Tamp the shorter course against a concrete block. Insert the lower rebars into the exposed splice area.

Figure 24 Splice on current course using tube as concrete form (left to right): a- Insert diagonal; b- Insert vertical; c- Both hooks fit within tube form on wall top.

If the rebars are inserted straight, add a 255 mm (10") long hook on each after inserting. Immediately insert the rebar further so that the hook is no more than 75 mm (3") above the course top. Each rebar should have at least 255 mm (10”) length embedded in concrete for good strength.

Pour concrete into the tube end to connect them (Figure 25a). Shake it down into the tube well and tuck the end under (Figure 25b).

The concrete does not need to be completely smooth on top (Figure 25c) since the next earthen course can conform to its shape. Lay barbed wire on the course immediately to connect to the splice. Do not continue building above the splice until the concrete is firm enough to survive tamping forces from above (4- 12 hours). When plastering this area tamp additional wall material or plaster in to fill any remaining gaps.

Figure 25 Pour splice on current course (left to right): a- Add concrete inside tube over rebar hooks; b- Shake concrete in place and tuck bag end under; c- Finished splice level with course.

Open Splice Connecting Upper and Lower Rebars

Vertical and/ or diagonal rebars inserted from the same course can also be connected to the hook of a higher rebar (Figure 26).

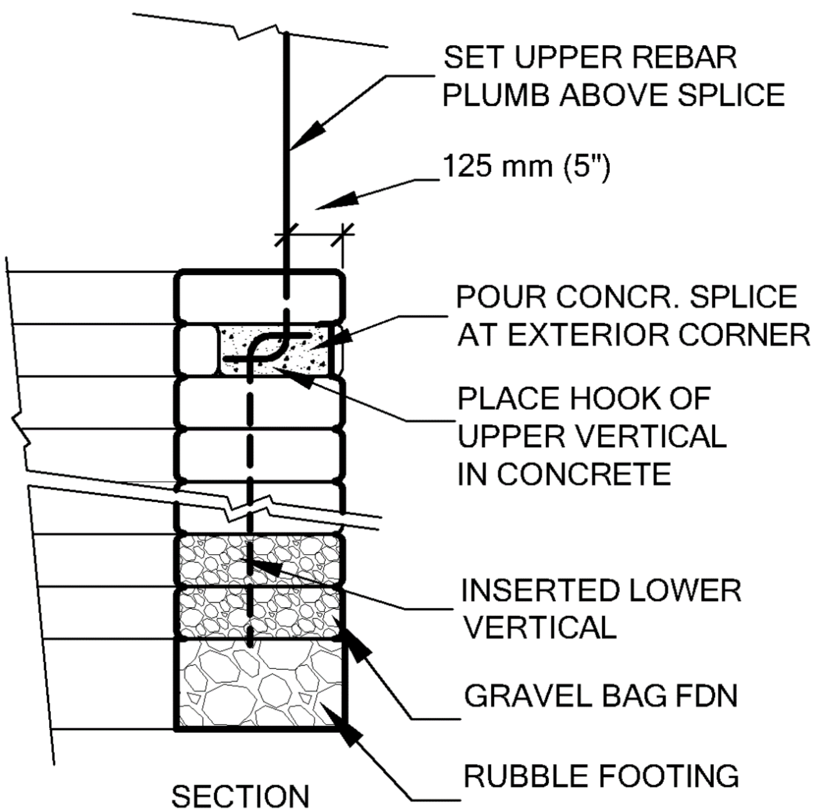


Figure 26: Barbed wire locations near punched-bag anchored rebar.

Start to build the course above the splice, but leave a gap 180 x 300 mm (7 x 12") at the end of the corner on the splice course exposed (Figure 27).

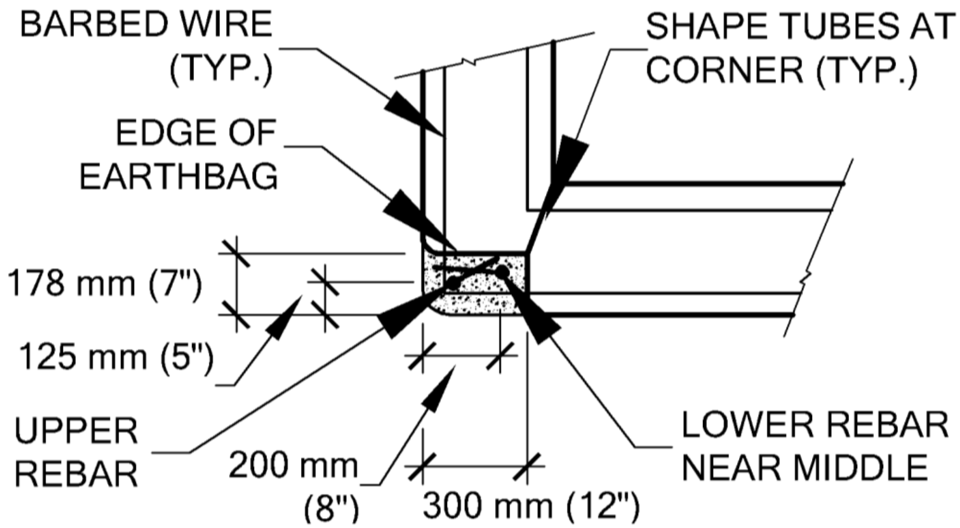


Figure 27 Use a narrow gap for an open concrete splice to connect upper and lower rebars.

At external corners the base-anchored rebar must be 125 mm (5") from one outside surface of the wall and 255 mm (10") from the other surface. Locate the upper rebar 125 mm (5") from both surfaces. Use bracing to support an upper rebar with a long hook in place or tie it to a short vertical pin inserted in the two courses below. Interlock the upper and lower rebar hooks and tie the upper rebar to the inserted lower one with wire.

A section of mesh tube or a form to hold the concrete allow inspection of the upper rebar placement. Pour the concrete a full course deep and recheck the upper vertical for plumb.

Construction above the splice continues by punching tubes and sliding them down over the rebar. Always start the tube length at the corner.

Run the barbed wire above the splice around the rebar.

When tamping around vertical rebars already anchored in place, be careful to maintain the rebar vertical and at the correct distance from the wall end and wall surface.

COVERED SPLICES

At exterior corners or wall ends, the upper rebar can be Inserted, reducing the number of new tube ends interrupting wall container continuity (Figure 28).

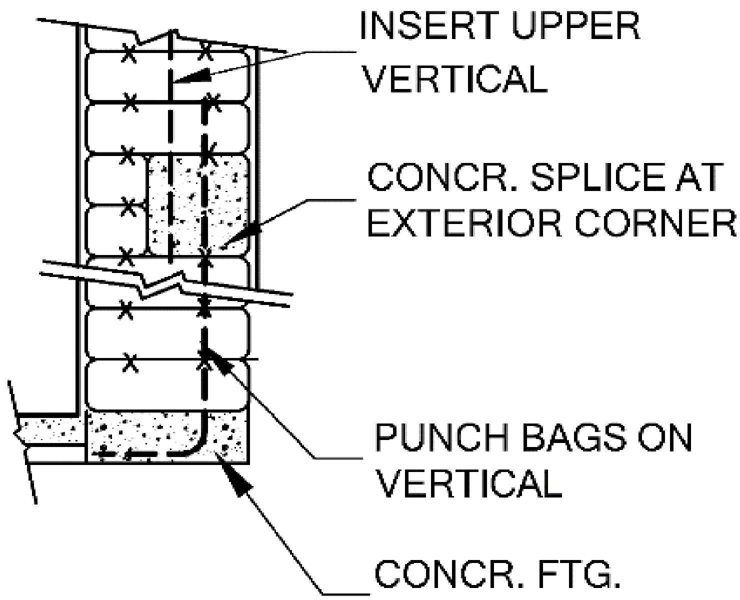


Figure 28 An upper rebar inserted into a covered splice bag two courses high, then the sandbag is emptied and filled with concrete.

But a covered splice must be larger to act as a viable target for the upper rebar, and takes more planning. Although only a 100- 150 mm (4- 6”) wide area of concrete is needed to connect the rebars, builders must be able to reliably pierce into the sandbag with a rebar inserted from many courses above.

The splice sandbag is 255 mm (10”) diameter and two courses high. Sew or staple a length of tube 510 mm (20”) long in to a lay-flat width of about 195 mm (7.75”). Punch it onto the lower rebar, which should extend through the sandbag and the course above the splice to support the upper course when the splice area is emptied of sand.

Mesh tubing can help to guide concrete into place near the back of the void space. A strong plastic tube (like used in erosion control straw wattles) may be more helpful than crocheted mesh (used to package vegetables). To allow barbed wire on both courses next to the splice to be embedded in the concrete, cut it near the corner, and poke it through the mesh to bury it in the concrete splice. Use a form half the height of the splice gap to keep a relatively dry mix of cement contained near the rebars.

STEPS TO MAKE A COVERED SPLICE

1 PREPARE: Locate the lower rebar 100- 175 mm (4”- 7”) from each of the outer edges of the walls at the corner. Build the wall to the bottom of the splice.

2 PLACE A MESH BAG: Place a mesh bag at least 510 mm (20”) long on the exposed rebar.

3 PLACE THE SANDBAG: Partially fill an upright fabric sandbag 255 mm (10”) in diameter. Cut a hole and lower the sandbag onto the lower rebar (Figure 29a). Fill with sand.

4 CONTINUE THE WALL: Fold the top of the sandbag over. Fill courses next to the sandbag. Insert the barbed wire through the mesh bag Figure 29b). Note- the lower rebar should extend above the sandbag. Build above the sandbag with corner overlaps (Figure 29c).

Figure 29 An upright sandbag for a covered splice (left to right): a- Insert the sandbag into the mesh tube; b- Build courses next to the sandbag; c- Add courses above splice to final wall height.

5 INSERT THE UPPER REBAR through the center of the corner to pierce the sandbag while the wall interior is damp. Let the wall dry several days.

6 PREPARE THE SPLICE GAP: Cut the sandbag, remove sand and fabric. Bend all exposed barbed wire into the gap space (Figure 30a). Hold a form in place with short nails in the exposed bags (Figure 30b).

7 ADD CONCRETE TO THE SPLICE: Pour concrete into the form using the mesh bag as a funnel. Squeeze the bag to place the concrete around the upper parts of the rebar (Figure 29b). Trim any excess mesh when you remove the form (Figure 30c). After drying, press damp wall fill material into any remaining gaps.

Figure 30 Making the splice (left to right): a- Remove sandbag fabric, b- Place form and use mesh to fill the top, c- Concrete splice with mesh trimmed.

REINFORCEMENT NEAR OPENINGS FOR MODERATE RISK

Because forces from along an entire length of building wall are concentrated between openings, the best quality of reinforcement detailing is needed for the panels between wall openings. A rule of thumb used for higher strength earthbag walls is to insert verticals every 1,2 m (4') on center minimum.

Note: more reinforcement is not always better. Do not space long rebars closer than 460 mm (18"). Shorter angled pins should be at least 380 mm (15") apart on average, since rebar too closely spaced in earthen walls can reduce wall strength.

Inserting Long Rebars

The longer an inserted rebar, the lower the end and any overlap with a separate piece occurs. Forces on walls from earthquakes multiply with higher distance from the foundation. A lower overlap may mean less wall damage in a serious earthquake. Next to door and window openings long rebars that extend well into the continuous walls below the openings reduce damage.

Rebar pieces as long as 2,1 m (7') are recommended near doorways. There are several tricks to inserting rebars longer than 1,5 m (5').

- Cut the tip at a sharp angle
- Have a helper hold a guide next to the wall and/ or use a level to check for plumb
- Hold the rebar in a narrow pipe a little shorter than the exposed rebar while hammering
- Use a tool made of a long capped pipe so that workers can pull the tool down around the rebar and insert lengths of steel that extend above the worker's heads

SPACED LAP REBARS

Standard grade resilient CE earthbag doesn't use as many lap rebars as low-cement CE for low seismic risk areas. Some builders will choose to splice all verticals next to window openings, and may only have spaced lap bars located in the middle of longer wall panels.

For those who overlap verticals near window openings, reinforcing steel embedded 150 mm (6") from edges should be spaced as far from their paired aligned verticals as the length of overlap (Figure 31). This is important to avoid overcrowding steel too close together. Use lap rebars long enough for the distance to the main vertical rebars.

TABLE 7: SPACE BETWEEN MAIN VERTICALS AND LAP BARS

Distance to vertical full-length rebar	Length of lap bar	How many courses above?
300 mm (12")	600 mm (24")	two
375 mm (15")	750 mm (30")	three but hammer 50 mm (2") below top
460 mm (18")	920 mm (36")	three

Build as many courses above the end of the lower rebar as needed to match the distance from the main rebar to the lap. Insert the lap rebar, then finish. Insert the lap rebar in a course as high above the lower rebar as it can be located in distance. Hammer it flush with the course top. Finish by inserting the upper rebar almost directly above the first one.

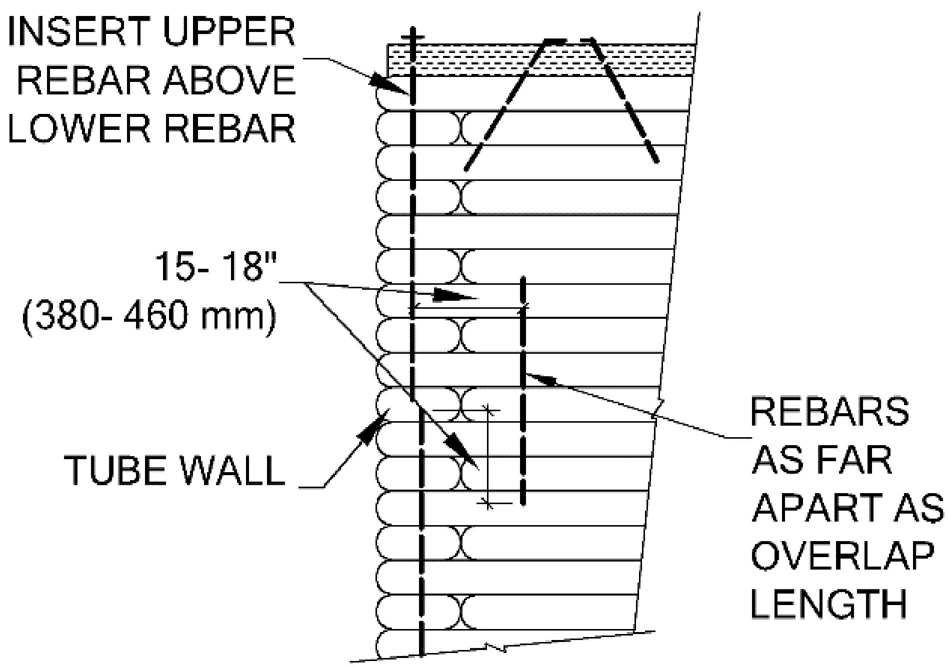


Figure 31 Improved overlapped inserted rebar technique uses a distant lap rebar.

OPENINGS

SPACE WALL OPENINGS

Separate inserted lengths of aligned vertical rebar need a lap rebar that overlaps both bars. Separate aligned rebar sets can share the shorter lap rebar if it is located between them. But do not crowd rebars too close in earthbag walls.

Aligned verticals each side of a window that extend three courses below the window sill can share the same lap rebar if the window is 600 mm (24”) wide or more. Narrower windows will need to have separate lap rebars each side of the adjacent aligned verticals. Aligned verticals on separate openings can also share a lap rebar between the openings.

Where wall intersections occur between openings larger distances of 1,2 m (48”) are needed for good rebar placement (Figure 32). Aligned vertical rebar in wall intersections should extend from bond beam to footing to unite wall intersections. Instead of including a lap rebar, use a different course location for the break between upper and lower pieces so that rebar next to the window and within the wall junction can act as laps for each other.

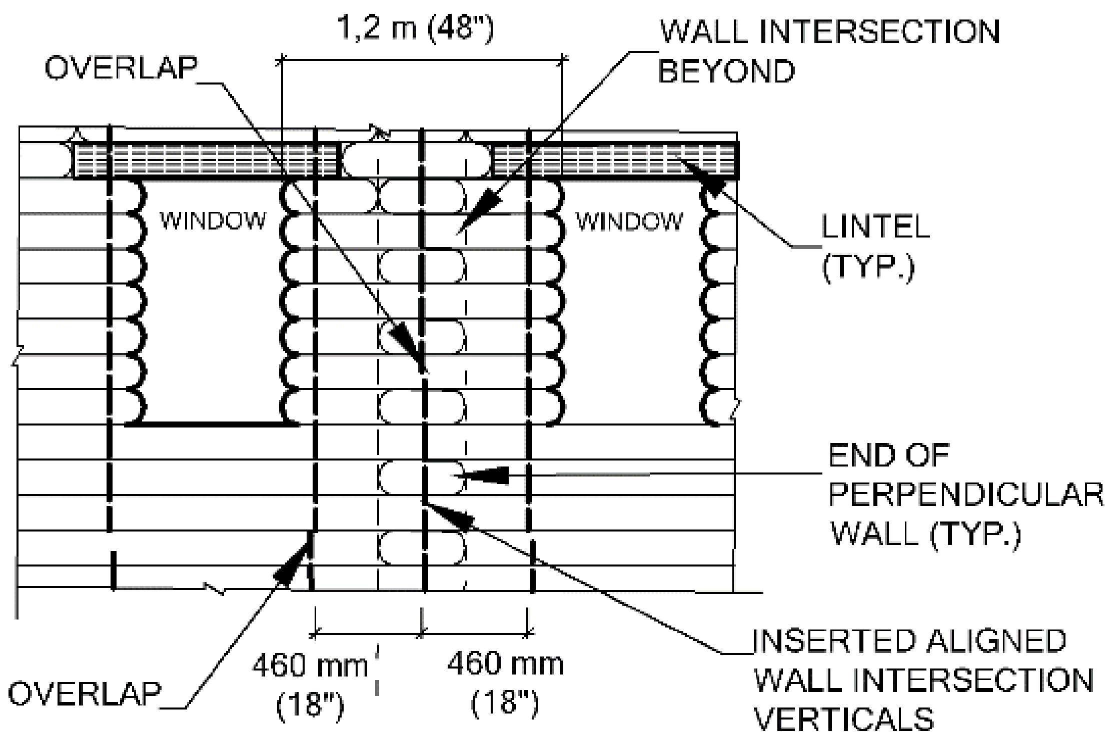


Figure 32: Use greater distance between openings when the area includes a perpendicular wall.

LINTELS

Lintel size and strength should relate to the span length and weight of wall above the opening, extending 300 mm (12”) or more each side of an opening. Wood lintels narrower than the width of the flat portion of the earthbag wall (255 mm/ 10”) should be placed on a 250 x 50 mm (2 x 10) bearing plate on the wall top to spread the weight out across the whole flat surface of the CE wall.

New Zealand’s earthen building guidelines recommend a single 100 x 300 mm (4 x 12) laid flat for spans of 900 mm (35”) or less where lintels support up to 1 m (39”) height of earth wall above. Three 100 x 100 mm (4 x 4)s nailed together can be used instead of the larger timber. For a span up to 1,5 m (5’) or less use a single 150 x 300 mm (6 x 12) laid flat or three 150 x 100 mm (4 x 6)s nailed together.

Use local building code for masonry buildings to choose lintels supporting less weight, and for reinforced concrete lintels.

For openings 1- 1,5 m (3’ 3”- 5’) wide drill holes for two or more D10 (3/8”) or smaller diameter vertical rebar pins between other holes in the lintel. These spikes can be nails with small heads but should extend 150 mm (6”) from the upper surface of the lintel. As the next earthbag course is filled, lift it and settle it onto these nails or pins.

INTERCONNECT LINTELS

Lintels connected to the bond beam reduce potential damage to walls next to openings. Standard grade resilient CE construction uses wooden lintels to connect separate rebars.

Drill one hole on each end of wooden lintels for driving a vertical rebar 150 mm (6”) beyond the edge of the window or doors. Insert a straight long rebar vertically down through each hole in the lintel into the courses at the window edges. Leave the rebar extending 410 mm (16”) above the top course.

Alternately punch and cut the courses above up to the bond beam level (Figure 33).

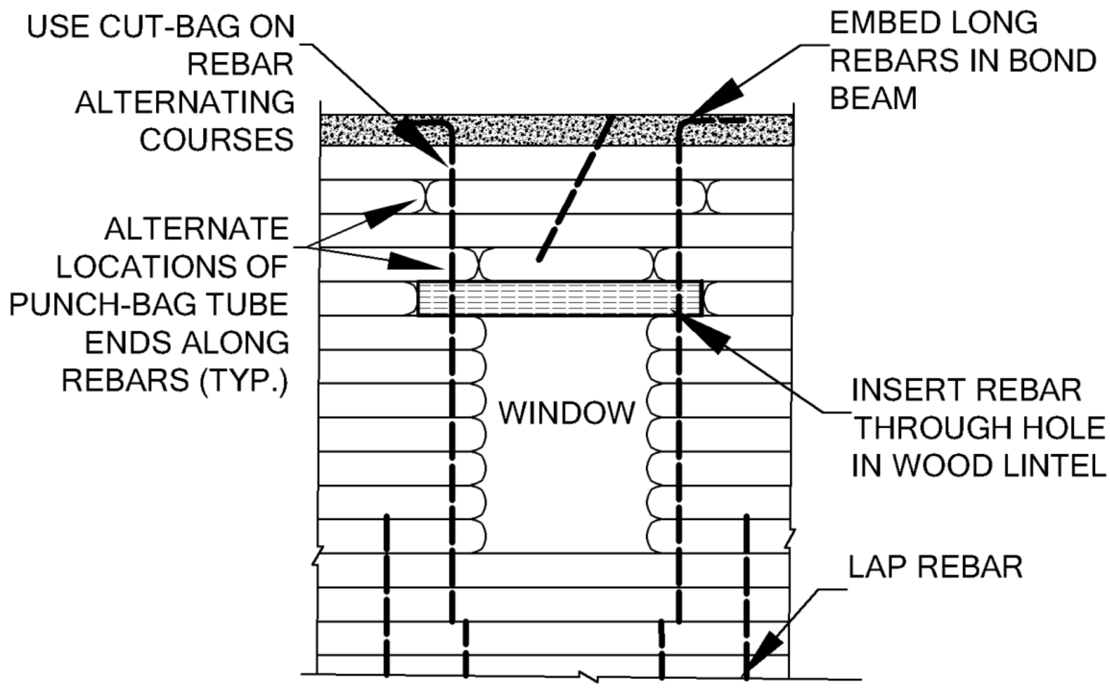


Figure 33: Vertical rebars adjacent to a window opening connect to the lintel.

Because doorways more effectively divide wall material, door lintels should have an open splice to attach rebar from the lintel to below the door sill. Punch the courses onto the vertical next to the door and slide the lintel down onto the vertical rebar. After courses above the lintel are built, bend the rebar hooks down to embed in the bond beam (Figure 34).

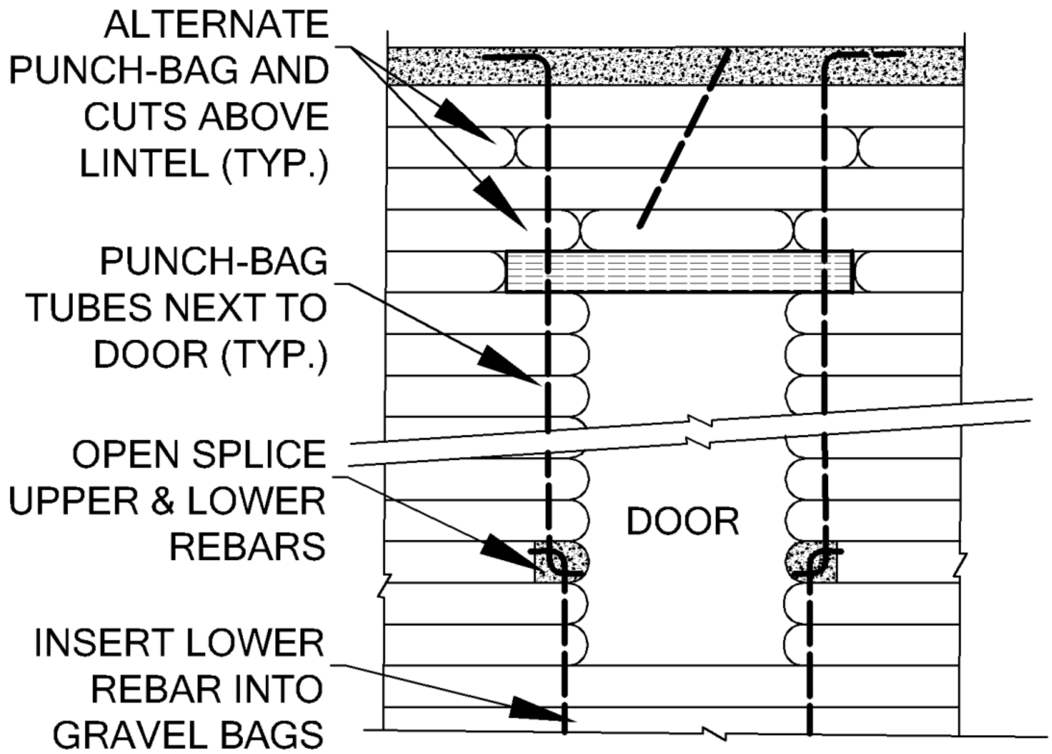


Figure 34: Splice vertical rebars next to doorways to provide vertical rebars extending below the door sill.

BOND BEAMS FOR MODERATE RISK

The bond beam must be sized for the wall thickness, type of roof and/ or loft and for the distance between bracing lines.

Because bond beams receive higher force levels at the wall tops than most other parts of building walls if they undergo an earthquake, the connections to the wall and to the roof above must be stronger than many builders expect. Check with local engineers instead of assuming that traditional construction should be used.

The concrete must embed tops of all pins as well as bent tops of vertical rebar 255 mm (10") or more long. Insert steel so the hooks will be contained within the depth and width of the bond beam.

Guidelines in New Zealand recommend bond beams 75% as wide as the wall, but standard earthbag courses built 125 mm (5") high have a flat top surface 67% the width of the completed wall.

Insert diagonal pins joining wall tops with bond beams while wall material is damp (within 2- 3 days of construction). Space pins that extend 600 mm (24") deep into the wall 600 mm (24") apart on average at alternating angles. Conventional earthbag relies on alternating angles of pins to hold the bond beam to the wall. Because resilient CE relies on bolts or strong hooks on tops of long, embedded vertical rebar, less angled pins may be needed.

WOOD BOND BEAMS

New Zealand's earth building guidelines do not recommend wood bond beams at this risk level unless they are connected to a structural diaphragm.

A diaphragm at the ceiling level helps buildings resist earthquake forces. It is a structure of ceiling joists and strong and strongly attached plywood or flooring. In some cases a diaphragm could consist only of welded steel tube. More information is contained in NZ Standards 4299, including specifications and examples of how this horizontal structure can increase allowable bracing line distances or reduce needed sizes of bond beams.

STEEL TUBE BOND BEAMS

Strong steel tube can be welded to form an integral bond beam and ceiling or loft diaphragm, but must be located with the inside of the tube near the center of the wall top so that vertical rebar and pins can be welded or bolted directly to the tubing. Because the tube will not cover 2/3 of the wall top, use strong strapping every foot from under the top two courses to integrate the bond beam to the upper courses and use stronger soil fill than the walls.

Reinforced Concrete Bond Beams

These standard-grade construction techniques for resilient CE earthbag should be used with a reinforced concrete bond beam.

New Zealand's earth building guidelines can be adapted to resilient CE earthbag with the consideration that CE is tougher and flexes more than adobe or rammed earth.

In its standard width CE is also 9% wider (and heavier) than the earthen walls specified for New Zealand. The following (Table 5) shows bracing distances 90% of the New Zealand recommendations for adobe or rammed earth in low risk areas:

Table 8: Reinforced Concrete Bond Beam Size Estimates for Single Story

Bond beam size	Rebar size	Maximum bracing distance with light roof
285 x 150 mm (6" x 11.2")	Two D16 (5/8 inch)	4,2 m (13'- 9")
285 x 175 mm (7" x 11.2")	Two D20 (0.9 inch)	5,7 m (18'- 9")

OPTIONAL IMPROVED WALL TECHNIQUES

Often careful detailing can increase strength without increasing cost significantly. It may depend on the attention to detail that workers and contractors are willing to invest in a project.

SPECIAL BARBED WIRE DETAILS

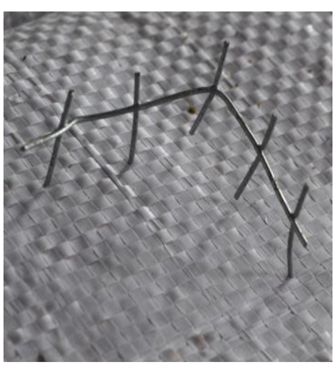
Because barbed wire transmits forces along walls, extra connection to the dried soil fill can strengthen corners or other stress points against damage.

PIN BARBED WIRE

Place pins cut from metal mesh (Figure 35a) over barbs on the wire. Pins with three or more teeth stand up between courses to embed in both lower and upper courses. Bend them just before use (or they will tangle together).

TIE BARBED WIRE

Cord also adds strength to resist any potential gapping or twisting at corners. Tie strands that follow the outer edge of the wall (Figure 35b). Use UV resistant cord and tie it on a barb cluster so that it cannot slide along the wire.



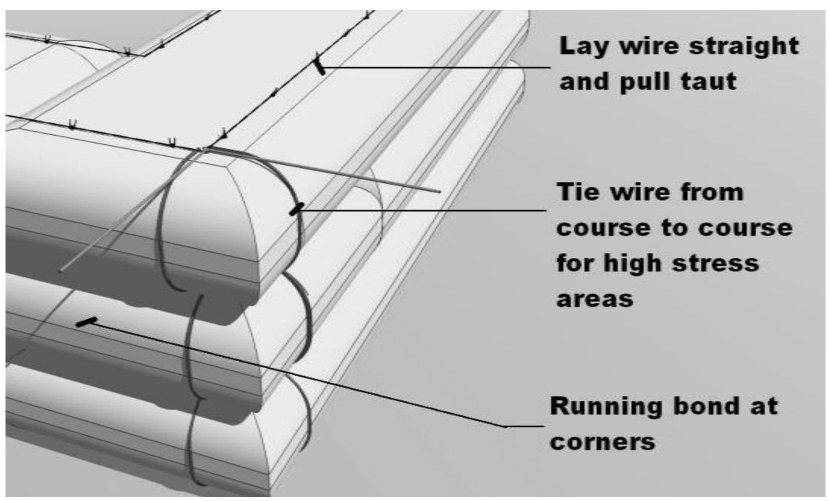


Figure 35 Add strength where barbed wire turns corners (left to right): a- Pins cut from wire mesh and bent can pierce upper and lower courses, b- Tie wire from bends in barbed wire out both sides and up to the next course.

STRONGER FILL INCLUSION

The compressive strength of dried soil fill determines how well wall masses resist cracking. Extra strength can be added to specific parts of walls where stresses concentrate, by increasing the proportion of strong clay.

Areas that will benefit from higher strength fill:

- the lowest course of building walls
- upper half of walls at corner rebar
- upper half of walls at wall intersections
- reinforced buttresses or piers

THICKENED CORNERS

Without extra steel or cement for stronger reinforcement, buildings can be strengthened by thickened walls.

Piers less than 1,8 m (6’) high provide more mass to make walls more stable, which can be helpful at wall corners. If bracing panel lengths can allow a limited 380 mm (15”) extension at corners, build it as a corner pier (Figure 36).

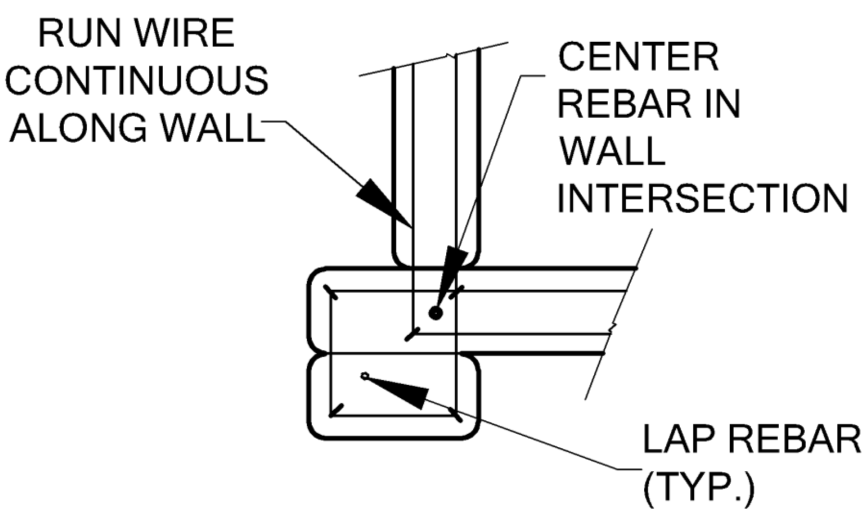


Figure 36 Corner pier

Plan ahead for piers or buttresses in the footings. Use inserted rebars in the center of the intersection between walls and piers or buttresses to unite these separate elements well.

SPLICED FORK

Wall intersections often occur at the middle of exterior building walls. Standard grade resilient CE only has stiff connections from vertical rebars to RC footings at wall corners. Forks use wall weight to hold wall intersections together during earthquake motion and to stiffen the response of a spliced rebar that is not base-anchored. Use a spliced fork for additional stiffening and resistance against warping where walls connect.

Build an open splice following directions on pages 37- 43. Add some diagonal rebars from the splice to create a fork (Figure 37).

Spliced forks can also add strength to buttresses or piers.

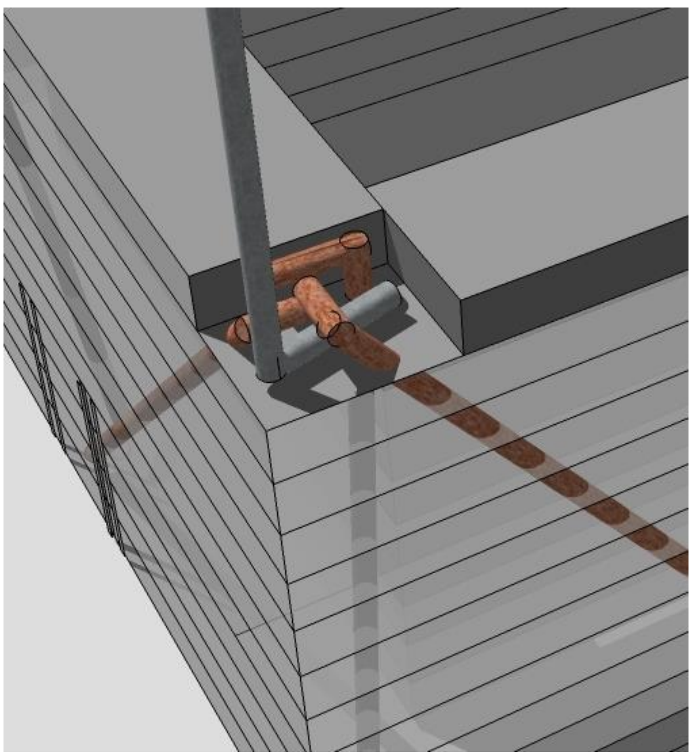


Figure 37 Forming space for spliced forks at corners to connect diagonal and vertical rebars.

Enough room must be left in the gap to insert the diagonals and for their hooks (Figure 38).

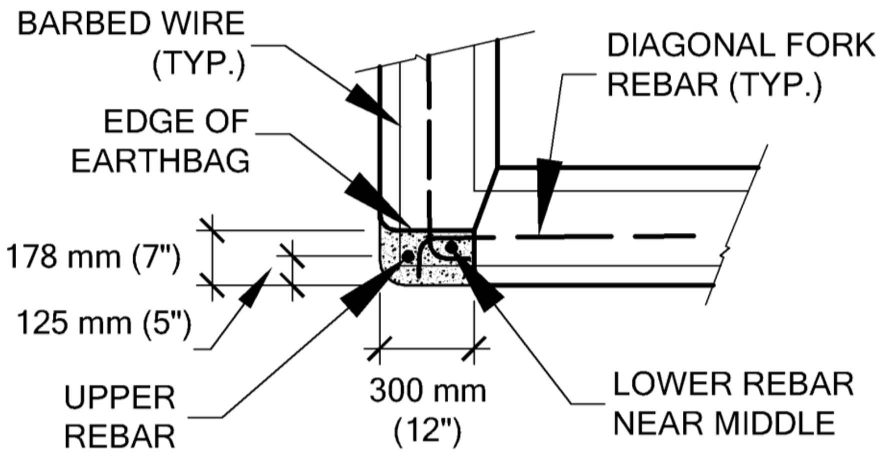


Figure 38 Reinforcement locations in a fork splice.

STEPS TO MAKE AN OPEN SPLICED FORK

1 PREPARE: Below the splice locate barbed wire 63 mm (2.5") from the outer edges of the walls at the corner. Build the wall to the bottom of the splice.

2 FORM THE SPACE: Build one course up to the edge of a gap space 180 x 300 mm (7 x 12") or larger at the corner.

3 INSERT THE LOWER REBARS into the earthbag course. Place the lower vertical toward the inner side of the gap, 125 mm (5") or more from the wall corner. Insert diagonals into each direction in the middle of the walls.

4 INSERT THE UPPER REBAR when ready to pour the concrete. Locate it 125 mm (5") from both sides of the corner. Attach the form, pour the concrete to the level of the adjacent courses and adjust the upper rebar for plumb.

5 CONTINUE THE WALL ABOVE THE SPLICE after the concrete has hardened. Cut holes in the tube ends using the punched-bag technique. Fill the punched tube 150- 200 mm (6- 8") deep and slide the tube over the exposed upper rebar. Re-firm the fill and finish filling

ABBREVIATIONS AND DEFINITIONS

BUTTRESS	A stub wall added perpendicular to a building wall to brace it. Often used on exterior walls, especially at corners or wall intersections
CE	Contained earth (earthbag built with damp cohesive soil fill) in bags or tubes
CG	Contained gravel a.k.a. gravel bag (water-resistant earthbag filled with gravel) in bags or short tubes
CS	Contained sand (low strength earthbag with loose fill or dry fill) in bags
Covered Splice	Section of concrete to connect lower rebars to an upper rebar in a void space below current course.
FDN	Foundation
Fork	Lower diagonal inserted rebars spliced to an upper rebar.
FTG	Footing
Lap Rebar	When separate rebars are inserted one directly over the other, a lap rebar overlaps them both.
Open Splice	Section of concrete to connect lower rebars together or an upper rebar to lower rebars. Concrete is poured below building above the splice level.
O.C.	On center (similar to at __ centres)
PIER	An area of thickened wall. This can be a repeating identical element where a wall is thickened for bracing purposes
STUB	A stub wall has only one end attached to another wall and lacks bracing
TYP.	Typical indicates that every where this element appears in the detail or plan it is the same