B103: BUILD HIGH STRENGTH RESILIENT CE EARTHBAG

Strip RC Footings for Moderate to High Risk

PATTI STOUTER, APRIL 2021

BUILDSIMPLE.ORG, ALBUQUERQUE, NM

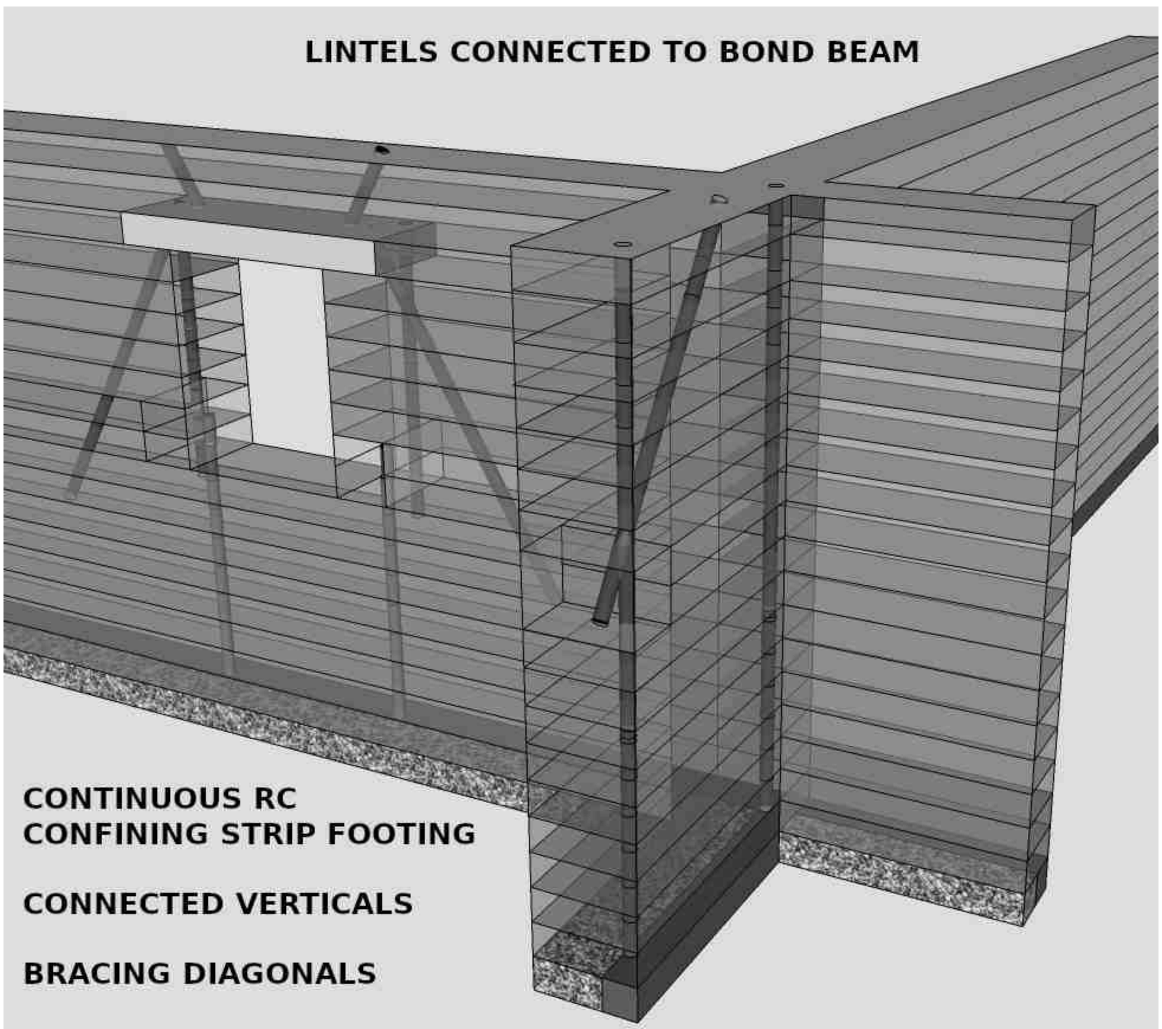

Figure 1: Vertical rebars can all be anchored in a strip of reinforced concrete.

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This document is dedicated to Owen Geiger for taking the time to teach and demonstrate earthbag worldwide. He encouraged natural builders to use earthbag, but also warned that earthquake forces need to be considered carefully.

Kelly and Zana Hart: thank you for encouragement, feedback and suggestions throughout the past ten years.

No engineer has specifically approved the construction detailing contained in this volume. But several have given invaluable input, including:

Dilendra Maharjan, Heatly Engineering

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Brandon Ross, Clemson University

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Thanks also to the Creator for giving subsoil and metal the qualities that allow us to create beautiful and safe buildings of earth.

1 INTRODUCTION

Conventional earthen buildings, if built carefully, are well suited to areas with minimal or no seismic risk. But where risk is higher, earthquakes often damage or destroy unreinforced buildings of earth, stone, or brick. Earthbag buildings on gravel bag footings have survived some earthquake motion better than conventional unreinforced masonry.

Earthbag buildings use gravel-filled bags as a water-resistant foundation with earthen courses above the finished floor level. Damp soil is poured into fabric bags or tubes used as forms. Bags or tubes are filled on the wall and laid down to form a running bond type of overlap. Fabric containers are closed at the end by tucking under or pinning with wire. Each course is tamped to consolidate into a 380 mm (15”) width and to level the surface.

Two strands of barbed wire are laid immediately on each course near wall edges. Vertical steel reinforcement is easily inserted through damp soil fill into the middle of walls. Rebar have traditionally been inserted at midwall height in 1,5 m (5’) lengths as straight sections, overlapped by pieces inserted from the wall top. A strong horizontal bond beam is attached to ends of rebar and to shorter rebar pins inserted at alternating diagonal angles.

A sticky first plaster layer is used to level deep nooks between courses. Finish plaster or stucco applied over mesh protects the walls from sun and water.

Earthbag Vs. Earthquakes

Conventional earthen buildings are suited to areas with minimal or no seismic risk. But in places with moderate to high risk earthquake forces often make earth buildings deadly.

Earthbag has been used in seismic risk areas as a low cost and low-cement way to build. Barbed wire between courses adds toughness and inserted rebar provides some stiffening. Conventional earthbag buildings have to date survived moderate earthquake forces- horizontal forces equal to 70% or less of gravity in Nepal’s 2015 quakes.

Earthbag is not magic. Testing shows that it can be damaged. Horizontal earthquake forces can exceed 170% of gravity. When wall strengths are inadequate for earthquake forces, doors and window frames can be broken and upper walls warped out of shape.

Communities want institutional buildings to *predictably* be usable after earthquakes. This booklet provides guidance for those planning to design buildings or test this material.

Conventional Earthbag Construction

Earthbag building requires a lot of heavy labor but few power tools, and few and low-cost manufactured materials. It is an immediate process with few steps of preparation. It is usually lightly reinforced with little advance planning.

High strength resilient CE (contained earth) on confined part-gravel bag foundations can survive higher horizontal forces than traditional earthbag. In shake table testing corner buttresses reduced motion in small samples by 25- 35%. Confining strips of RC around natural footings resist damage from collapse of site soil. Base-anchored vertical reinforcement may increase wall shear strength as much as 50% higher than separate inserted reinforcement lengths. Rebar trussing in the buttresses or wall corners can provide much higher strengths where needed.

The details included in this system of reinforcement require a moderate amount of pre-planning. Steel vertical reinforcement must be located correctly in narrow strip footings. Special details at corners, buttresses and wall openings are built in as the walls rise.

In areas with moderate or higher 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

Soil fill strength and type of finish plaster influence overall wall strength. If soil fill is weaker than 1,7 MPa (250 psi) or cannot be proven that strong, contained earth walls may not be appropriate for important buildings. Stronger soil fill of 2,1 Mpa (300 psi) is recommended for high risk areas.

Finish plaster or stucco layers are a critical part of earthbag reinforcement. Earthen or lime plasters ensure walls with high ductility (flexibility that resists vibration damage). Cement stucco may increase wall in-plane strength and also reduce ductility.

These details for high strength resilient CE earthbag can be used in areas with seismic risk of 0.4 g- 0.85 g pga at 2% pe (or 0.08- 0.17 g pga at 10% pe if designers can check for adequate lengths of bracing walls. They may perform best in buildings that are:

- one story or one earthen story with a light upper level
- <600 m^2 (6458 s.f.) total
- built on firm ground (> 600 mm/ 2' from a downhill slope that is not easily erodible or likely to subside)

These details may also be used in areas with seismic risk of above 0.85 g pga at 2% pe (or 0.17 pga at 10% pe) in buildings designed by an engineer.

What is 'High' Seismic Risk?

Earthquake risk can only be estimated. Scientists use history of earthquakes and local bedrock conditions to estimate likely force levels. Then government officials choose what level of motion they will expect buildings to resist.

Sketch maps below (Figure 2) compare rough estimates of general seismic risk levels to earthen wall strength. In white areas old types of earthen construction are generally safe. The darker the gray color, the more dangerous traditional earthen buildings can be.

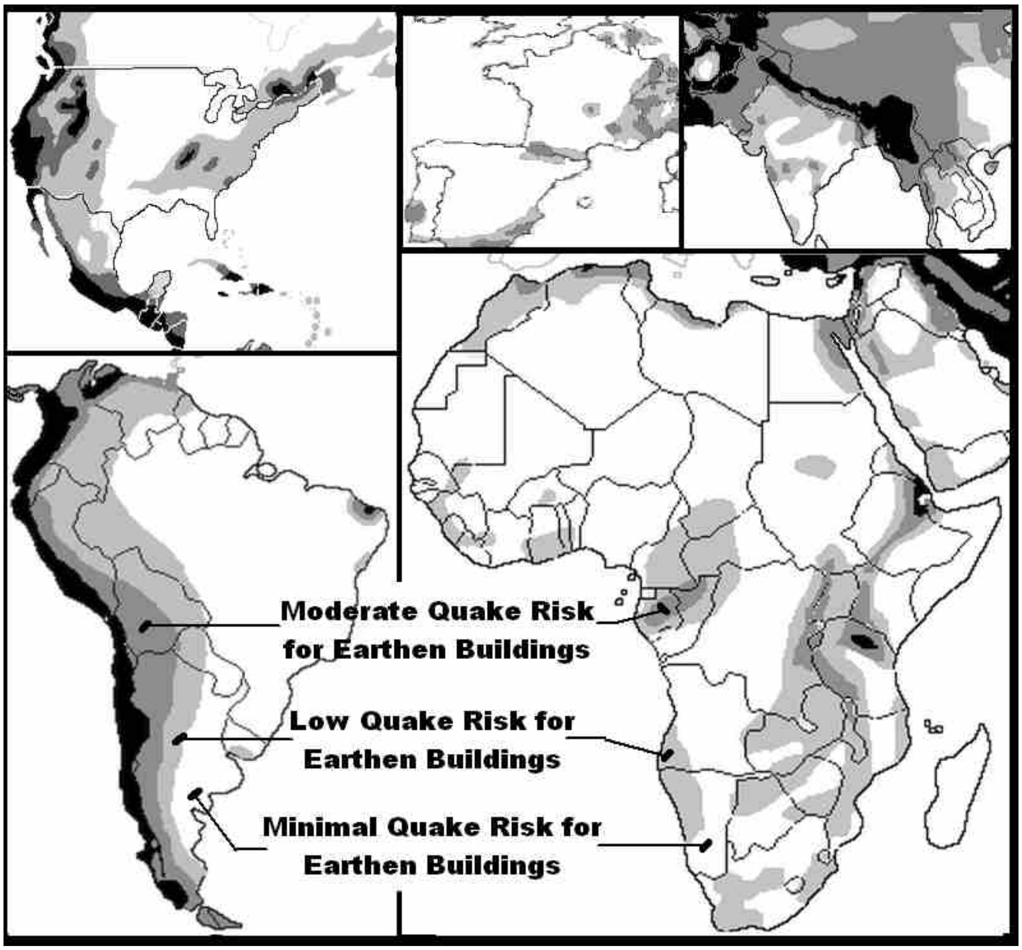

Figure 2: Approximate locations of earthquake risk relative to earthen wall strength.

Light gray areas often have conventional earthen buildings damaged or destroyed by ground motion, but some types of earthen buildings without reinforcement are safe if the building plans and details follow very careful guidelines.

In dark gray areas earthen buildings must be reinforced and risk levels range from moderate to high. The closer a site is to areas shown as black, the higher its seismic risk.

Black areas have very high seismic risk. Because earthen buildings are heavy and have modest wall strength, only very special earthen buildings can be safe.

This author uses risk levels that match earthen building guidelines developed for New Zealand, so that their structural-design based details and specifications can be adapted.

Moderate to high risk is:

0.6- 1.7 g (gravity) peak ground acceleration (pga)
occurring in 'Ss' pulses of 0.2 second (that cause the most damage to low-rise buildings)

with a likelihood of 2% probability of excedance (pe) in 50 years.

Risk levels are complicated. Sites with soft soil or seasonal high groundwater face higher risk while areas with bedrock or stony ground may experience lower motion than nearby sites. Ask an engineer or professor of engineering for advice if local government has not defined risk.

Professionals talk about risk using different scales of measurement. In some areas they use 10% in 50 year probability of excedance, as seen in the online world maps in the Global Earthquake Model (GEM)[1]. Users can zoom in on areas of the GEM maps, but they report similar acceleration speed or pga levels with different numbers than the map above.

To compare categrories used in Figure 2 to the GEM maps or others using 10% probability (such as European building code maps):

MODERATE RISK	**PE (PROBABILITY OF EXCEDANCE)**	**MEASUREMENT**	**COLOR**
BuildSimple maps[2]	2% in 50 years	0.6- 8.5 g pga	dark gray near light gray
GEM hazard maps	10% in 50 years	0.12- 0.17 g pga	yellow
HIGH RISK:			
BuildSimple maps[2]	2% in 50 years	0.86- 1.7 g pga	dark gray near black
GEM hazard maps	10% in 50 years	0.18- 0.34 g pga	yellow-orange
VERY HIGH RISK:			
BuildSimple maps[2]	2% in 50 years	$\geq$1.7 g pga	black
GEM hazard maps	10% in 50 years	$\geq$0.35 g pga	yellow-orange

[1] Global Earthquake Hazard and Risk Model online at https://www.globalquakemodel.org/gem
[2] https://buildsimple.org/Resources >D21 Sketch Maps for Seismic Risk

What Strength of Quake Can Earthbag Survive?

It depends on the building plan.

Buildings survive earthquakes only when the structure is strong enough both for the intensity of ground motion and for the exact building layout. The question is not what earthbag can survive, but how to figure out if a specific building plan built of a specific type of earthbag can survive.

Strength and ductility of the wall +

Long enough bracing panels in the building plan +

Foundation strength

= Building safety for a certain level of quake motion

Lone straight walls can tip over in earthquakes. Heavy walls like earthbag need corners to prop them up. If every structural wall in both of the main directions connected to long enough solid wall sections can lean on its neighbors during an earthquake it will survive.

If the solid ‘bracing’ wall sections are a little too short, they may warp into diamond shapes but still hold up their neighboring walls. Earthbag walls subjected to quake forces too strong may be deformed and some door frames may be broken. Parts of the building may be damaged, have reduced resistance to stress and ultimately need some rebuilding.

If we know actual CE wall strength and design with long enough bracing panels, buildings won’t be damaged in earthquakes.

What we Know about CE Wall Strength

Previous test results underestimate resilient CE earthbag strength. Research with cohesive, dried soil fill used either 60% scale earth-plastered samples with scale-reduced rebar or 80% scale unplastered samples with faulty reinforcement. Scale-reduced samples showed proportional improvements from soil strength, rebar connection and plaster improvements, but not exact full-size wall performance. Compared together the smaller and larger tests proved:

1. Meshed plaster provides a large proportion of earthbag’s strength
2. Stronger soil fills increase wall toughness and strength
3. Improved reinforcement connections increase both yield and maximum strength
4. Embedded rebar (not external) reduces deformation and strength at yield

5. Rebar stiffly base-anchored reduces deformation and increases strength the most

Prelimanary results from current research of 80% scale walls with better attachments and cement stucco confirm rough estimates used in this document. Full data will be published online as soon as possible.

Earthbag wall strength can be compared to strengths required in existing building guidelines for conventional earthen walls. New Zealand's *Earth Buildings not Requiring Specific Engineering* (NZS 4299:1998) may be a helpful resource. Walls of reinforced earth block are specified for moderate to high seismic risk areas and of unreinforced earth block for low risk areas.

Information from NZS 4299 should be adapted to respond to the 9% thicker wall width and thus slightly heavier wall weight per length for earthbag than considered in that document for the thickest earth block walls. Some types of CE may need reduced bracing line distances or added piers between bracing lines to stiffen the very flexible CE walls.

Earthbag builders hoping to resist forces from 0.6- 0.85 g at 2% pe (or 0.12- 0.17g at 10% pe) may refer to NZS 4299 construction details for reinforced earth block walls, although CE earthbag may not always need full-width reinforced concrete footings.

The New Zealand codes consider that unreinforced adobe walls are not ductile and their fully reinforced walls have some ductility. Ductility measures how well a material can survive by deforming without quick strength decline and/ or collapse.

Rough estimates (Table 1) based on previous structural testing of CE samples compare different types of earthbag to New Zealand's required earthen wall strength and ductility. These estimates multiply approximate strength by considered ductility, since the American Society of Civil Engineering building code reduces the level of force a building is required to face by dividing it by the ductility factor. A factor of 3 means a building only has to face 33% as high forces.

Even considering possible high ductility, earthbag buildings may not perform as well under strong seismic events as the heavily reinforced adobe walls specified in NZS 4299.

Buildings are often designed so that expected force levels will not exceed the material's yield strength (strength before starting to deform more quickly). Designing for yield strength avoids any possibility of wall and roof collapse in materials that suddenly lose strength at maximum force. It also prevents extensive rebuilding needed when sheetrock-covered interior walls are damaged.

Earthbag walls' plaster finish begins to crack after yield strength, and is easily repaired. Since earthbag walls continue to deform without losing material long after maximum strength is passed, they may potentially be designed to resist forces near maximum.

The strength of earthen walls required to survive very high earthquake risk is much higher than that needed to survive moderately high risk levels. When building in any area with seismic risk above 0.85 g at 2% pe (or 0.17 g at 10% pe), resilient CE earthbag designers should seek engineering advice to determine the wall strength to use when sizing needed bracing panels. Full engineering design may reduce construction costs and will result in safer buildings.

TABLE 1: ROUGH ESTIMATION OF POSSIBLE PERFORMANCE OF IMPROVED EARTHBAG COMPARED TO ADOBE[1]

	Ductility of CE Tests	Considered CE Ductility	CE Yield Strength: Adobe	CE Maximum Strength: Adobe
Resilient CE earthbag (fill strength)	**compared to unreinforced adobe (in NZ <0.6 g risk/ 2% pe)**			
Overlap-reinf. CE (strong[2])	3 x higher	2 x higher	130%	130%
Connected-vertical CE (medium[3])	2.5 x higher	2 x higher	113%	130%
Connected-vertical CE (strong)	3.5 x higher	2 x higher	143%	188%
Resilient CE earthbag	**compared to reinforced adobe (in NZ <1.7 g risk/ 2% pe)**			
Connected-vertical CE (strong)	1.75 x higher	1.5 x higher	36%	47%

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

[2] Medium fill 1,38- 1,59 MPa (200- 230 psi)

[3] Strong fill 1,70- 2,07 MPa (250- 300 psi)

STRATEGIES TO DESIGN RESILIENT CE BUILDINGS

Use compact shapes such as square or squarish buildings, not long narrow buildings. Buildings should not have one side more than 3 times longer than the other. Use symmetrical, simple shapes, not L-shaped or irregular buildings. Keep parts of adjacent buildings 460 mm (18”) or more apart so walls or roof edges don’t hammer each other in an earthquake.

The taller an earthen wall, the thicker it should be for good stability to resist toppling over. Curving walls can add strength to rectangular buildings, even if the building has straight sides too.

Never build heavy earthen wall portions or elements like chimneys or gables above the bond beam. Space window and door openings evenly without clustering them. Keep them far enough apart so that the building is more wall than opening.

Plan carefully and build thoughtfully. Draw elevations showing reinforcement to check for regular reinforcement spacing and prevent conflicts.

More information and a system to check bracing walls based on the New Zealand earth building guidelines will be supplied in *D91 Design Resilient CE Earthbag Buildings for Seismic Risk* online at BuildSimple.org/Resources.

Always check online for the most recent structural testing results that match your exact planned wall construction. If structural test results appear out of date, email pstouter@buildsimple.org to ask whether there is any newer data.

RESILIENT CE EARTHBAG REINFORCEMENT SYSTEMS

Earthbag is useful in rural parts of the developing world where keeping costs low is critical. Unless details use low-cost materials in simple ways, they are not practical.

Many builders fear that stronger earthbag may become too stiff. Test results to date indicate that earthbag is a material that warps too easily. Earthbag can be much stiffer without being brittle. Greater strength and stiffness brings its performance closer to that of a strong steel spring that can recoil without damage.

Other myths that builders or designers may need to unlearn include:

- A jar or sedimentation test to see that soil fill has a good proportion of sand and clay does not prove actual strength in the wall. Neither will standing on a full-size dried unit or driving a truck wheel onto it.
- Although adding gravel to some soils may increase compressive strength, earthbag walls have an excess of compressive strength but need more shear or tensile strength. Gravel in fill does not increase needed wall strength.
- Barbed wire can not be replaced by short pins between courses. Barbed wire provides tensile strength along the wall as well as a unique flexible system of bridging between the low-friction fabric surfaces on courses.
- Vertical strapping can not increase wall strength, since it often becomes loose as CE courses dry out and shrink slightly. Vertical strapping on gravel courses can increase wall strength and provides a good attachment for plaster mesh.
- Mesh for plaster should not be only nailed into the surfaces of the bags. Even lightweight mesh can share wall stresses efficiently if it is tied to barbed wire, footing strapping, and to the bond beam.

- Unconnected reinforcement elements (like barbed wire strands running across the wall) do not help to increase wall strength.

Systems with Uniform Strength

This system of high strength reinforcement has been chosen for maximum strength. Other resilient CE reinforcement systems with lower strength are described in pdfs online at BuildSimple.org/ Resources.

Buildings begin to fail when a single weak element breaks or separates first. All parts of a building must be chosen with similar strengths, and connected with care. The most important differences between the Low-cement, Standard Grade, and High Strength systems of reinforcement are their foundation construction (Table 2).

Low-cement CE has no rigid footings. Standard Grade uses spot footings only at corners. High Strength uses a continuous reinforced concrete (RC) strip footing that confines a wider gravel bag base. In addition to increasing resistance to foundation damage if adjacent soil subsides during an earthquake, RC footings multiply the strength of the rebars anchored in them. Vertical rebars in Low-Cement CE walls can easily rotate as the different courses slide at bed-joints. Vertical rebars stiffly anchored at their base can resist higher forces that lead to their bending ('yielding'), so Standard Grade CE buildings develop these higher strengths at corners. In High Strength CE buildings these higher reinforcement strengths are repeated throughout the wall lengths because all vertical rebars can be anchored in the strip footings. In addition, corner buttresses used with High Strength CE increase wall stability as well as hold rebar bracing to stiffen wall corners by triangular groupings of steel.

Once the footing includes a complete reinforced concrete confining strip, all vertical steel can be base-anchored, and potential types of reinforcement multiply. Strength of high strength resilient CE can vary widely if optional extra-strength reinforcement details are used to increase building resistance to seismic events. Options include full rebar webs embedded in wall panels or buttresses, welded steel door or window frames connected to vertical steel, and more. For details and advice about locating cut and punched-bag techniques on tubes, see *B104 Extra Strength Resilient CE Details.*

These details increase the cost of steel and time required to build somewhat. Builders without code restrictions or requirements from investors may not be willing to use the more complex techniques shown in this booklet and in the extra strength details booklet. But builders and owners who do invest time and some additional material costs to use a stronger reinforcement system will create stronger natural buildings.

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	Continuous verticals
Corners	Open splice + fork	Continuous verticals	Continuous verticals, rebar bracing and buttress
Wall Inter-sections	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 one vertical to bond bm	Continuous or connected to bond beam
Doorways	Connect to bond bm	Connect verticals to bond bm	Continuous or connected to bond beam
Lintels	Wood	RC or wood	RC or wood
Bond Beam	Wood	RC or steel (wood with ceiling diaphragm)	RC

Note about dimensions

To make this information accessible for builders worldwide, both metric and imperial units are used. Somr illustrations contain only imperial units because they require less room. Some approximate measurements have both metric and imperial units rounded even though they are not exactly equal.

2 MATERIALS FOR RESILIENT CE EARTHBAG

Earthbag building walls are more than 95% natural soil fill. The manufactured materials used, including fabric tubes, wire, cord and rebar, are common and widely available.

CONTAINED EARTH (CE)

Take care when choosing soil fill because for every 15 m (50') of building wall workers will need to transport, stir and lift almost 27 tons (30 US tons) of it.

Use subsoil. Leave valuable topsoil for agriculture. If a handful of soil stirred into a cup of water leaves material floating on top of the water, it includes organic material found in topsoil. Dig deeper for your fill, under the topsoil.

Natural soil fill can contain gravel but must be cohesive enough to hold together when dried. First check potential soils for cohesion using instructions online for hand texturing. A sandy loam or loam makes construction easy. A clay loam or sandy clay work well if the moisture level can be carefully controlled.

The most important quality for earthbag is how the fill acts in a bag. If a very gritty soil doesn't stick together well in hand testing, try tamping it in a bag. The soil inside should hold together. After it dries for 24 hours, use a piece of metal under it and turn the bag gently over. Cohesive soil with some strength is usually firm enough after a day to turn without the fill inside breaking up or crumbling.

Soil fill may be cohesive enough for earthbag. But to create high quality resilient CE for a hazardous area soil must be proven strong enough. Unless building soil is tested by an engineer, or purchased from a source that has already tested it, estimate fill strength with field soil tests or better, using small samples that can be dried and tested within a day.

New Zealand requires 1,3 Mpa (190 psi) compressive strength fill for standard grade block or rammed walls, but with CE better strength comes from stronger fill, such as 2,1 MPa (300 psi) soil.

Soil samples can only be tested when completely dry. Estimate strength with fist-sized samples that can be dried in a day. Some small samples can be crushed underfoot (Figures 3a,b) or others crushed with a 20 L (5 gallon) bucket of dirt on a simple lever to estimate strength (Figure 3c).

Find information online at BuildSimple.org/Resources on how to test 3 cm balls *(pdf B30)* or fist sized samples *(pdf D31)* to estimate soil compressive strength.

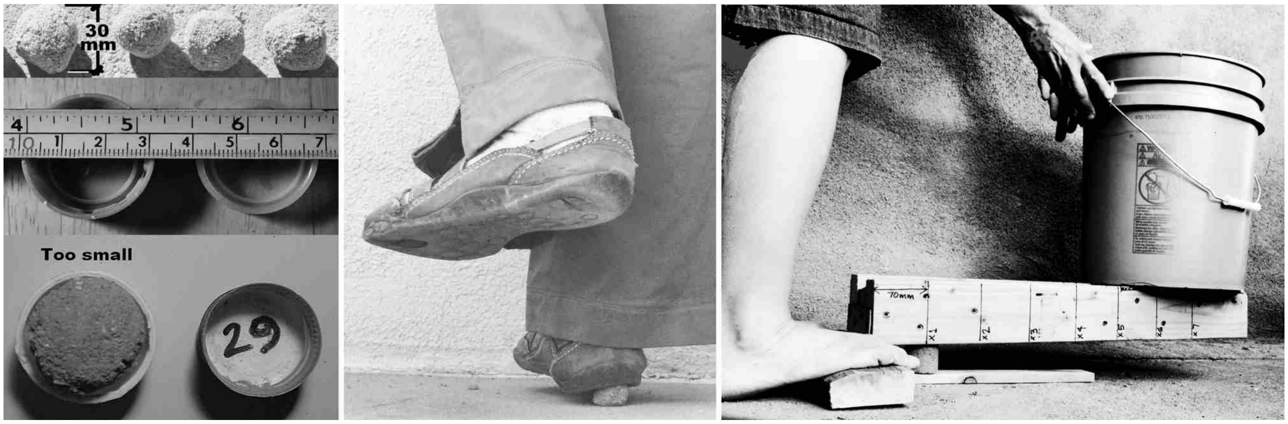

Figure 3 Estimating soil strength with small samples (left to right): a- Small balls can be compared to measured bottle caps to check for accurate size; b- Small soil balls can be crushed underfoot; c- Samples made in toilet paper tube forms can be crushed under a bucket of soil on a small wooden lever.

Stabilized Earthen Fill

Chemical stabilizers like Portland cement can increase the strength of wall masses, but thick earthbag walls require a very large amount of cement or other chemical. Stabilizers cause walls to harden in less than an hour and prevent inserting rebars. Labor is increased to measure and mix fill, and material must be built quickly or discarded.

Stabilized cohesive soil fill can be used for water-resistant base courses where gravel is not available, but has less potential for damping vibrations than gravel. It is also more difficult to include any type of inserted pins to unify these courses or connect them to ‘raw’ unstabilized courses above.

Gravel bags

Foundation walls of gravel fill provide moisture resistance and a capillary break to stop damp seeping upward. Short tubes or bags are filled after doubling them.

Reinforced Concrete

Resilient CE walls have enough ductility and toughness to survive on flexible wire-bound gravel bag base courses. But some reinforced concrete (RC) is needed in footings so that base-anchored steel rebars can reduce wall deformation significantly. 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.

Use as little concrete as possible, but always use clean washed sand and mix it in recommended proportions that include enough Portland cement.

Containers

Smooth woven fabric of flat polypropylene strands is most commonly used for earthbag. Breathable PP material allows earthen masses inside the fabric containers to dry out gradually and creates a smooth, low-friction fabric surface between courses.

Flexible barbed wire barbs and embedded steel rebar bridging the fabric surfaces at course bed-joints create a composite layered wall of metal and natural soil that can flex.

Use good condition fabric and protect containers from sun damage by plastering early- in the tropics or at high altitudes within 2 weeks. 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. But after the wall fill dries the container fabric is very important to prevent material loss if walls are damaged. Intact fabric containers hold the material in place and keep walls standing.

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

Mesh tubes can be used for CE earthbag but the damp fill unites through the mesh containers between courses. These monolithic ‘hiperadobe’ walls in crocheted mesh tubes (like vegetable bags) flex less than ordinary CE in smooth woven fabric tubes and may have higher strength against warping or bulging damage to walls. 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.

Plaster adheres well to the textured wall surface of extruded dried soil and non-biodegradable mesh, but lacks the air gaps between solid woven fabric and dried soil that may reduce damage from surface dampening for conventional earthbag.

Container Sizes

Measure tube sizes 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 produces taller courses.

460 mm (18”) tubes can produce either:

Wall thickness	Course before Tamping	Course after Tamping
380 mm (15”)	130 mm (6”) high	125 mm (5”) high
370 mm (14.5”)	178 mm (7”) high	150 mm (6”) high

Reinforcement

Reinforcement embedded inside earthen walls may last for generations if it is non-biodegradable. Embedded reinforcement should not be bamboo or other natural materials.

For increased longevity in areas with highly acid or alkaline soils, consider coating rebar in contact with soil with a rust-resistant but non-slippery paint before building.

Fiberglass or basalt rebar lack surface texturing for good bond. Do not use bars that cannot be bent to produce critical end hooks or welded to add top bolts or cross-pieces.

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, and keeps its strength if bent in a 50 mm (2") radius. With stiff base anchorage in spot RC footings, larger diameter steel can contribute its full strength to walls.

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 in areas subject to higher forces (between the middle of windows and the course above the lintels) could possibly increase resistance to bulging and/ or warping damage.

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 should cinch tight and not slip (like a trucker's hitch). For vertical strapping on gravel courses fiberglass packaging straps with a sealing tool may be a stronger alternative.

OTHER MATERIALS

PLASTER MESH plays a critical role in overall wall strength. Don't use chicken wire which decays in contact with plasters. Plastic geomesh or fencing mesh is costly. This author recommends weak plastic bird netting or fishing net which transmits 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. They can be wetted if allowed to dry between wettings. In damp climates use a good roof overhang to reduce the amount of wetting. Plaster made from hydraulic lime allows earthen walls to dry better than cement stucco which holds dampness. Consider using lime or earthen plaster on an upper interior area of all raw earthen walls in humid regions if the majority of the surfaces are finished with cement stucco.

Use a sticky first plaster layer to level the 75 mm (3”) deep nooks between courses. If the finish coat will be cement stucco, use a sticky earthen plaster stabilized with 3- 8% Portland cement or hydraulic lime. Stabilized earthen plaster reduces future stucco damage because it shrinks and swells with temperature changes similar to stucco.

Bond beams

All earthen walls must be carefully connected under a strong horizontal bond beam. The bond beam and its connections are the most important structural elements of your building, because forces are multiplied at the tops of heavy walls. Never build any heavy earthen wall portions (like chimneys or gable walls) above the bond beam.

Although wood bond beams are often used in lower risk areas, use a concrete bond beam for highest strength. Hooks of vertical rebars are easier to embed well in concrete poured around them than to connect to wood elements.

Welded steel tube can be used for a bond beam if it is combined with a steel ceiling diaphragm for added strength. Connections to the earthen wall courses will be critical. Read about diaphragms in NZS 4299 or ask an engineer for assistance.

Attach hurricane straps or connectors in the bond beam in regions subject to high winds. The winds are unlikely to blow your walls over, but losing the roof leads to moisture damage to the walls.

3 BASIC EARTHBAG CONSTRUCTION

For those new to earthbag construction, review the Earthbag Information slide shows *(B1- B5)* 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 online at the Naturalhouses youtube channel show accepted practices.

But before building in seismic risk areas, also look at examples of earthbag built in Nepal since 2015. Long tubes, high courses and quality construction used by the NGOs building in these risky areas has set new quality standards, such as seen in Figure 4.

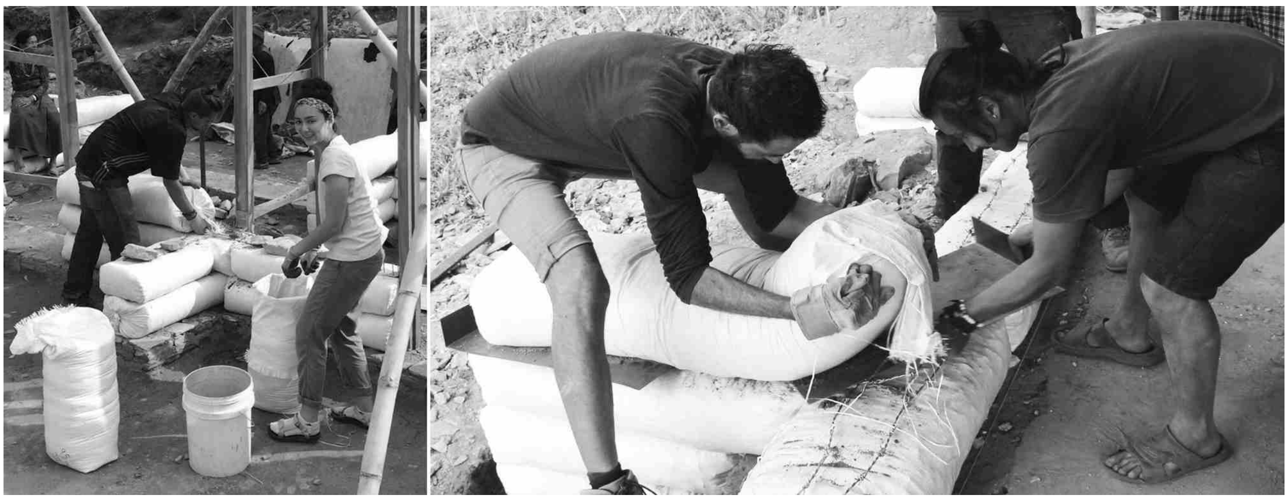

Figure 4 Earthbag in Nepal (left to right): a- 150 mm (6") high tamped tubes (T. Nillson used by permission); b- Building a buttress (First Steps Himalaya used by permission).

Earthbag construction is a heavy, time consuming process. Poor quality detailing is hard for novice builders to avoid. Check walls for plumb and straightness often.

DON'T:	**BECAUSE:**
underfill bags or tubes	too much wire per wall height increases costs
	thin courses have weaker dried fill masses
leave tube seams outside	requires a lot of plaster to cover
leave bulges at corners	requires a lot of plaster to cover
lay wavy barbed wire	wire doesn't add to wall strength until pulled taut

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 wall tops are damp.

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

Where wooden elements must be attached, use velcro nailer plates every 2nd or third course (Figure 5a).

Vertical integration between courses comes from the barbed wire barbs embedding in soil fill and from any embedded rebars. Vertical strapping unites base wall courses with gravel fill, but is not helpful over three or more contained earth courses.

BARBED WIRE ON CE

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 5b) 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.

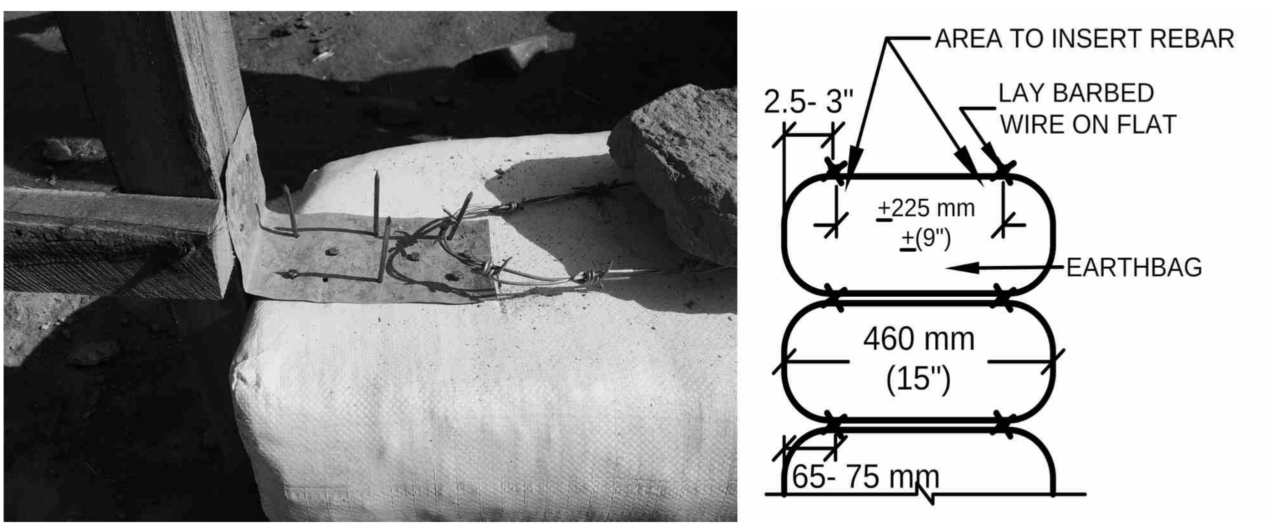

Figure 5: Earthbag connections (left to right): a- Velcro nailer connects wood frame to earthen wall material and to barbed wire (T. Nillson, used by permission); b- Barbed wire location on the flat course top near rounded course edges.

End barbed wire strands in the middle of a building side with at least a 600 mm (24") overlap (Figure 6a). At the end of a stub wall or near a wall opening, turn wire along the end and return into the wall (Figure 6b).

NEVER END A BARBED WIRE STRAND AT A WALL CORNER

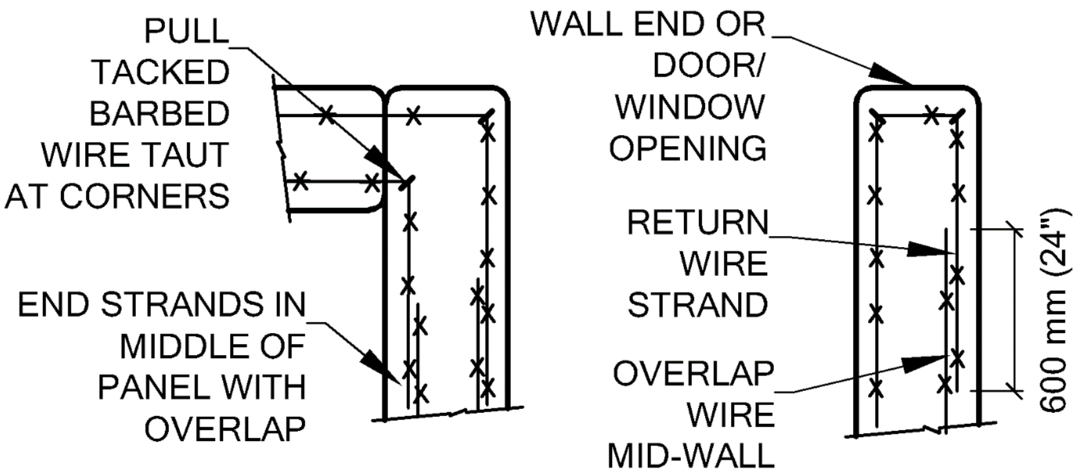

Figure 6 (left to right): a- Always run barbed wire continuous around corners and locate strand ends in middle of walls; b- Run barbed wire around wall end or opening edge and return.

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

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

Unite wall intersections and corners strongly with tube overlaps, inserted rebars and barbed wire. Alternate the direction of tubes at corners to provide good running bond. Lay barbed wire to unite the separate wall segments. The strand near the exterior of the wall may receive higher stresses and should usually run continuous around the building exterior.

Openings

Structural earthen walls must be more wall than openings.

Narrow windows are better than 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 on earthen walls extend 300 mm (12”) past the opening on both sides to distribute weight from above the lintel to a wide area next to the opening.

Steel Rebar Reinforcement

Rebar have traditionally been inserted in 1,5 m (5’) lengths as straight sections. Upper lengths have hooks bent 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 barbed wire. Diagonal reinforcement can be inserted at an angle, but must be centered and vertical relative to the thickness of the wall.

Plaster mesh

Attach mesh firmly to all walls from base to wall top. Tie mesh to vertical strapping on gravel bag base walls and to tie cords attached to barbed wire. At the wall top pull mesh over exposed rebar and embed it 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.

Cement stucco does not stick well to the fabric. Instead, under a cement stucco finish layer, use a sticky earthen plaster stabilized with 3- 8% Portland cement and/ 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, causing less cracking after the stucco is fully dry.

Bond beams

All earthen walls must be carefully connected under a strong horizontal bond beam. Form the concrete bond beam on the flat top of the top course. Bend all exposed rebar hooks down to embed in the concrete.

PART II: HIGH STRENGTH RESILIENT REINFORCEMENT SYSTEM

High strength resilient CE earthbag detailing (Figure 7) uses more and stiffer connections than other kinds of CE, creating a reinforcement grid of:

- A confining RC strip that surrounds gravel bag footings
- Vertical pins anchored in the RC footing strip
- Vertical rebars anchored in the RC footing that connect from wall base to bond beam at corners, doorways and wall intersections

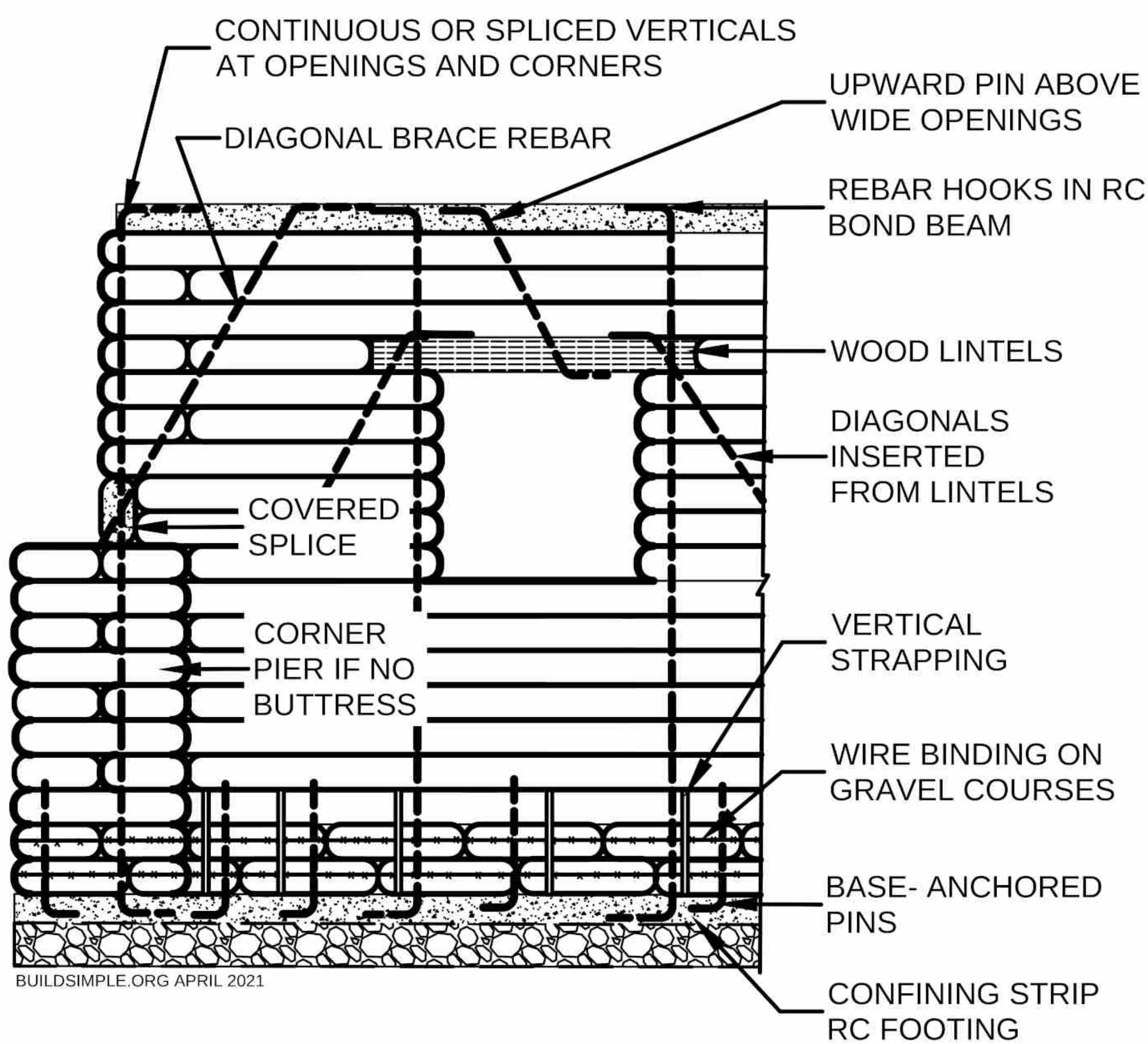

Figure 7 Improved reinforcement system for highest strength on RC strip footings.

Corners benefit from stronger elements including:

- Diagonal rebars spliced to verticals for bracing at one or more sides at corners
- At least one buttress at all external corners, or a corner pier

The minimum corner detailing involves either a buttress on one side of a corner or a corner pier to half of the story height. Either of these two options keep the wall material embedding the corner vertical rebar protected from mechanical damage.

With high strength resilient CE, openings can be well connected to wall material above and alongside by:

- Diagonal rebars inserted through the lintels to adjacent wall
- Upward pins from the lintel up into the wall above the opening

High strength CE forms a good basis for special detailing to increase wall strength. Openings can integrate stiffly welded steel forms into the wall reinforcement. Corners with buttresses can include embedded rebar with horizontals to form doubled braces or even full rebar truss webbing. Doubled braces can also be integrated next to door or tall window openings. For ways to increase strength of high strength resilient CE earthbag, refer to *B104 Extra Strength Resilient CE Details* online at BuildSimple.org/ Resources.

4 FOOTINGS FOR MODERATE TO HIGH RISK

Reinforced concrete (RC) in foundations is critical to resist damage from stronger earthquakes. Surprisingly horizontal force on a wall panel often causes it to disconnect and rotate, crushing the bottom edge and breaking it away from adjacent wall areas.

RC footings connect more weight to wall tops to resist this uplift, and the bottom hook of vertical rebar stiffens it against wall warping or bulging.

Unite a confining RC strip strongly to a gravel bag inner ring. Use gravel bags alone for foundations of many interior walls.

Because resilient CE walls' toughness allows them to recover from more twisting or bulging than most masonry walls, CE wall footings can allow some vertical flexing. Strength in footings comes from the size of the steel reinforcement more than from the depth or width of concrete. Footings 125 mm (5") deep may be less stiff against vertical motion than thicker footings, possibly allowing walls and footings to flex rather than break if powerful earthquakes include much vertical motion.

Buildings on subsoil that is easy to dig may need wider footings to spread out the heavy wall weight onto a larger area, since earthen walls often weigh twice as much as concrete block walls.

Any subsoil that is occasionally soaked from high tides or possible flooding should be discussed with an engineer to be sure that a heavy building won't be likely to tilt or sink if a quake happens when the soil is wet. Buildings on highly erodable soil, near a growing erosion channel, or that straddle across two different types of soil may need more strongly reinforced footings.

Confining RC Strip Footings

The confining strip of RC surrounds the entire building, poured around a narrow gravel bag footing strip (Figure 8). Use a concrete strip at least 180 mm (7") wide. Together with the gravel bag the total footing width should be 50 mm (2") wider than the earthbag wall.

Use wide gravel bags under interior walls with no adjacent reinforced concrete strip.

Reinforcement in concrete footings can be similar to what New Zealand recommends for earthen buildings for higher risk (NZS 4299:1998- pp. 35- 49)- three or four D16 (5/8" diameter) horizontal rebars continuous connected by R10 (3/8") stirrups every 400 mm (16"). Place single long bent rebars at corners, and overlap steel 600 mm (24"). Use 50 mm (2") of cover at sides and top and 75 mm (3") at the footing bottom.

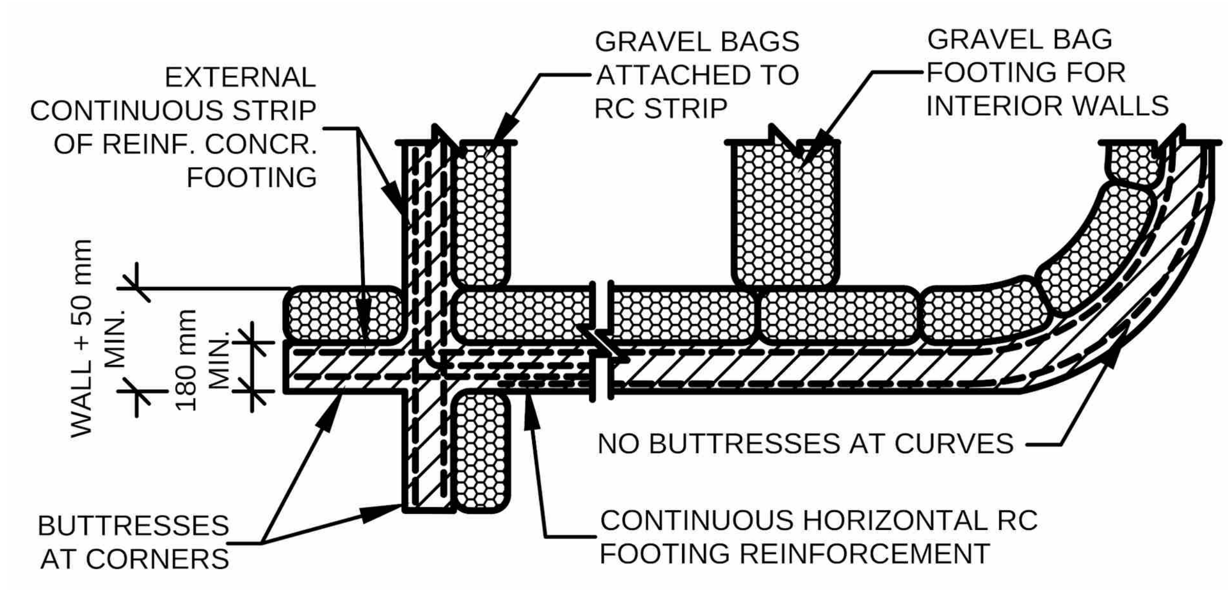

Figure 8: Confining reinforced concrete (RC) strip footing poured around gravel footing course.

Leave undisturbed subsoil or compacted fill next to the inner edge of the footing so gravel bags are held by the concrete strip against the edge of the trench (Figure 9).

Connect RC to gravel bags with strapping laid under gravel units and around the horizontal rebars in the concrete footing. Use one or two pieces of non-biodegradable cord on each separate gravel bag or 200 mm (8") wide strips of geogrid for extra strength at corner buttresses and at wall intersections.

Include vertical pins every 600 mm (24") in the concrete extending at least 255 mm (10") upward. Place vertical rebar at every wall corner, intersection, and near the edges of every wall opening with horizontal hooks at least 255 mm (10") long. After concrete is poured and cured, unite gravel to concrete by tying the strapping around the gravel bags and the concrete strip.

Mesh tubing for gravel units next to the RC strip allows poured concrete to embed the gravel containers. Strong extruded mesh tube like that used in erosion control wattles allows longer gravel units than possible with common size fabric bags, and may not need to be doubled like fabric bags.

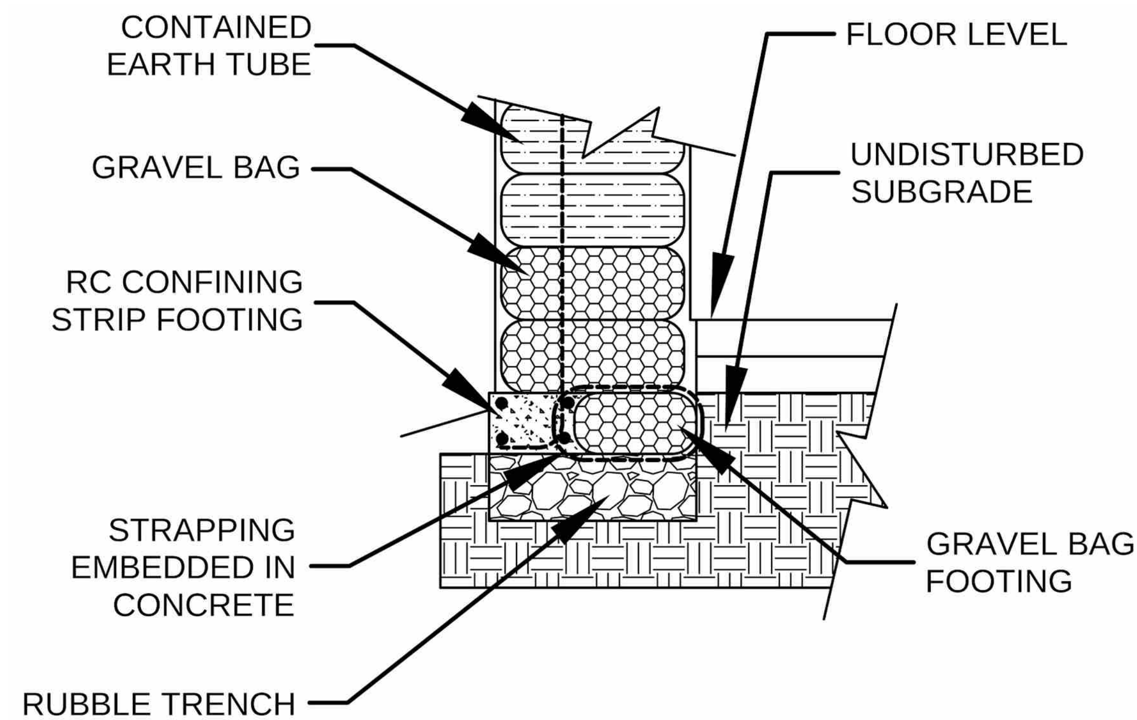

Figure 9: Section through RC strip footing strapped to gravel bags.

Connecting Gravel Bag Interior Walls to RC Footings

Embed bent ends of barbed wire used for gravel bag footing courses in the RC strip and/ or any spot footings to unite the separate materials.

RC Spot Footings

Use stiffly base-anchored vertical rebar at major intersections of interior walls. Anchor them in 910 mm (3') square reinforced concrete spot footings at most intersections in buildings larger than 90 m^2 (1000 s.f.) or with more than four rooms (Figure 10a).

Locating Vertical Rebar in RC Footings

Most vertical rebars are located near the external surfaces of the earthen building wall (Figure 10b) and anchored in the reinforced concrete confining strip footing. A standard 125 mm (5") setback from wall surfaces to vertical rebar allows barbed wire to bend around the rebar in many locations, with rebar deeply enough embedded in the soil fill.

Builders can use splices to connect upper and lower verticals instead of continuous rebars, but lower rebars must be located leaving room for upper verticals to be near the external corner. The upper wall receives higher forces and should have the barbed wire bent around the upper rebar length base-anchored in the splice.

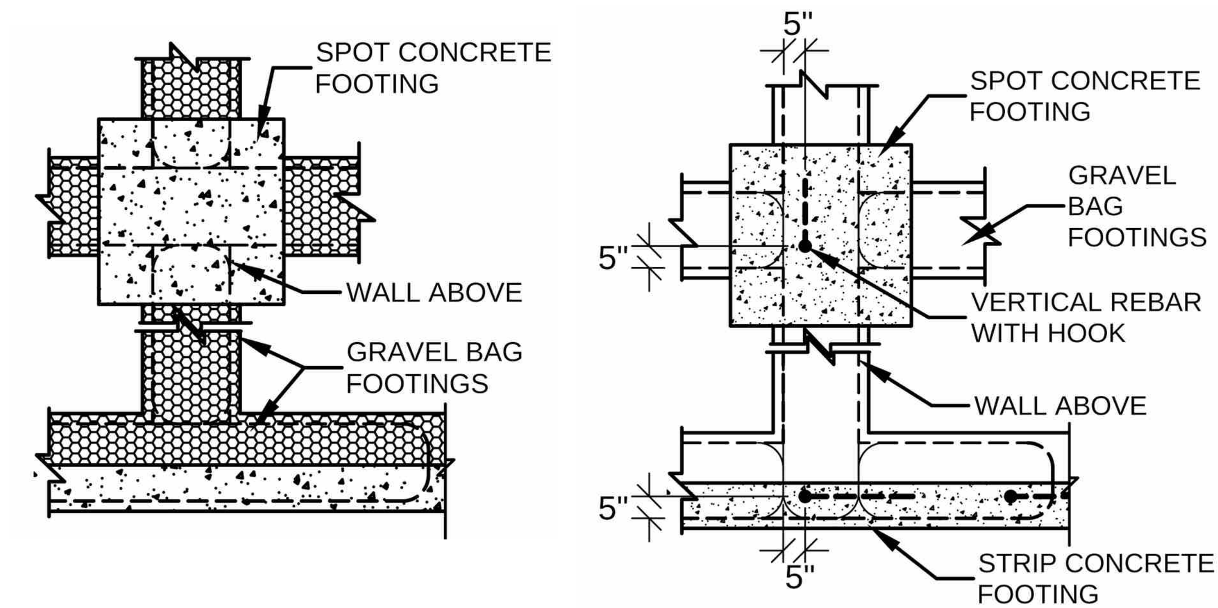

Figure 10 Details of RC spot and strip footings (left to right): a- Locate spot footings at intersections of major interior walls; b- Locate vertical rebar 125 mm (5”) in from surfaces of contained earth walls above to provide good embedment of steel in earthen fill.

Where forms or ‘bucks’ will be used at doorways, windows, or the ends of stub walls, rebars can be located 230 mm (9”) from the form so that a standard tamping tool can fit between the rebar and the form, unless this causes rebar crowding in the wall. Use a piece of 100 x 100 (4 x 4) wood to tamp between rebar that is close to the form.

FULL RC FOOTINGS

Full-width reinforced concrete (RC) footings may be needed in locations with more risk of subsoil loss:

- near steep slopes or erosion gullies
- in light, poorly compacted soils (sometimes found where streams widen out at the base of hills or mountains)
- on very sticky clay soils that crack when dry
- in areas where cracked pavement or foundations, or trees or posts on slopes leaning are common

Wider footings may also be needed on subsoil that is too easy to dig. Footing width spreads building weight out over a strip of soil as wide as the footing. Earthbag building walls weigh twice as much as concrete block, so extra wide footings are sometimes needed. Ask an engineer whether wider footings can be created out of gravel bags under the confining strip, or if a full-width RC footing is needed.

5 EMBEDDED REINFORCEMENT FOR MODERATE TO HIGH RISK

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

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. Tamped courses must consolidate without dry crumbs loose in the fabric containers at edges or corners.

In rainy regions, cover the soil pile when not in use. Fill that is too damp becomes too sticky to shovel easily and if ‘jellied,’ it can be impossible to tamp until it dries a little.

Better Bonding with Fill

Continuous high-quality connections between steel and soil fill is important.

Place barbed wire and pins on each course immediately after tamping for good bond. Rebar must be embedded. Insert as soon as the highest course pierced is tamped.

Walls are strongest with rebar embedded inside dried soil material

The ideal time to hammer steel into earthbag walls is within two to three weeks of laying the lowest course that will be pierced. Although interiors of courses dry slowly for months, the edges of every course begin to dry soon after construction.

Best Wall Continuity

Fine-grained connections spread out forces before they concentrate at levels that can damage earthen walls.

Use tubes as long as possible in walls. For one course run all east-west walls continuous through the corners or wall crossings. At the next run all north-south walls continuous (compare Figures 10a and 10b).

Get the most strength from barbed wire by straightening the wire, pulling it taut along straight walls. Run one strand on every course continuous around the external walls as far as possible. End barbed wire strands with at least a 600 mm (24") overlap that does not occur at corners or wall openings.

Bend wire sharply at corners (Figure 11a). Tack it in place at bends without rebar (Figure 11b, c) with electrician’s staples. For extra strength make wire mesh pins cut from strips of mesh that can connect upper and lower courses together. Cut each pin with three or more teeth but don’t bend them until placing them. Pins tangle together if bent ahead of time.

Figure 11 Hold barbed wire in place (left to right): a- Wrap around a vertical rebar; b- Tack wire at corners with an electrician's staple; d- Tack with pins cut from wire mesh.

TIED BARBED WIRE

For added toughness on external walls, use ties on all barbed wire strands near the external wall surface that bend without a rebar (Figure 12). Tie a strand of uv-resistant cord or wire on where the barbed wire strand bends (if possible at a barb). After the next course is built and wire laid, pull the cord up and tie the cord to the wire on the course above.

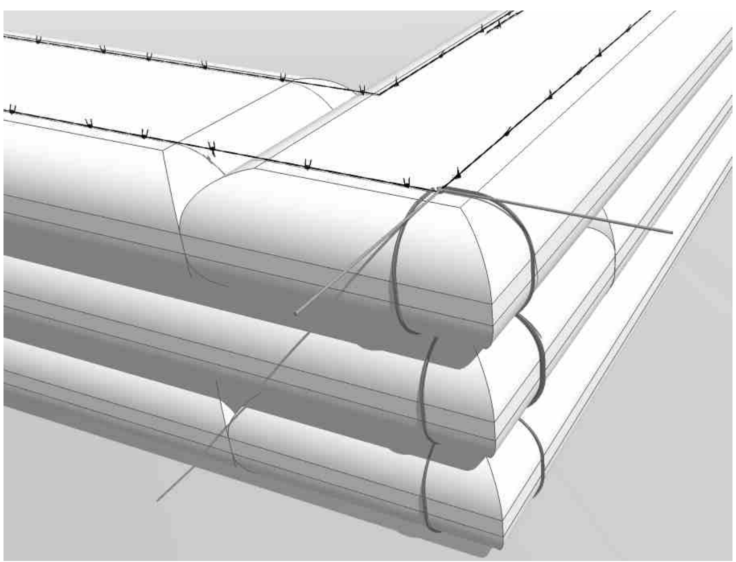

Figure 12: Hold barbed wire firmly in place and prevent gapping with ties at corners and intersections.

Each barb point can transmit stress, so longer wires benefit most from tying.

Run straight lengths of wire continuous on interior walls out across the exterior walls where they connect (Figure 13). Pin wires at crossings. At the end of a stub wall or near a wall opening, turn wire and return into the wall.

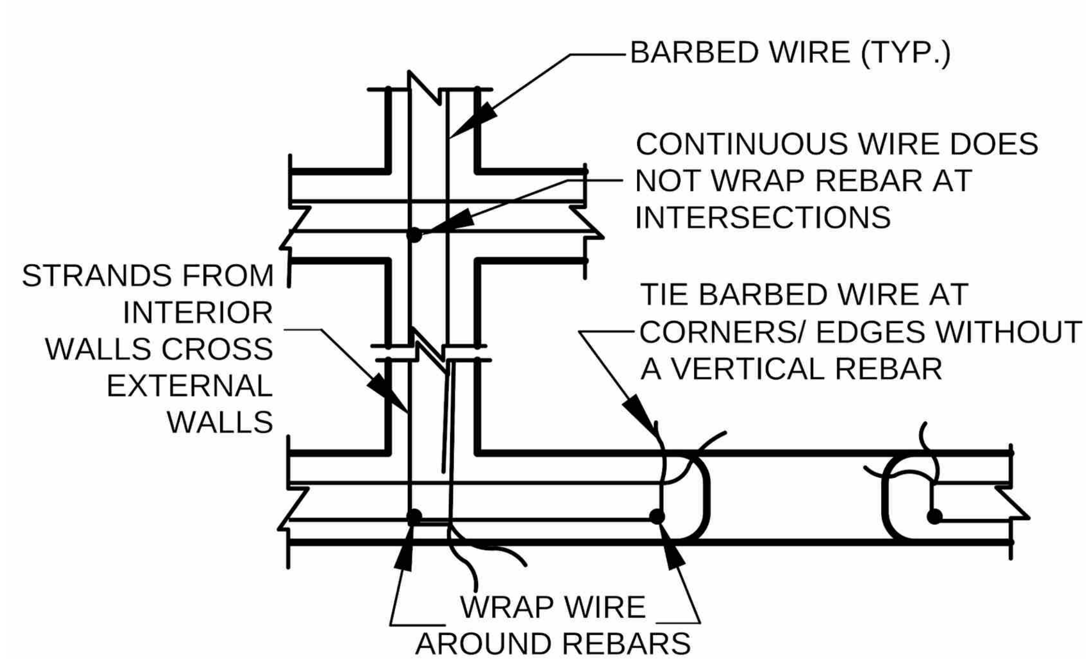

Figure 13: Run barbed wire continuous around corners and near wall ends or openings.

Connecting Buttresses and Piers

Buttresses (short added bracing walls) require extra care to lay wire. At corners, bend the external wall strand around the corner. Run the interior strands on the exterior walls straight out into corner buttresses, and turn back alongside the outer wall wire (Figure 14).

Some small buildings with few or small windows in areas with seismic risk close to 0.6 g at 2% pe (~0.17 g at 10% pe) may not need the extra bracing capacity offered by buttresses at both corners.

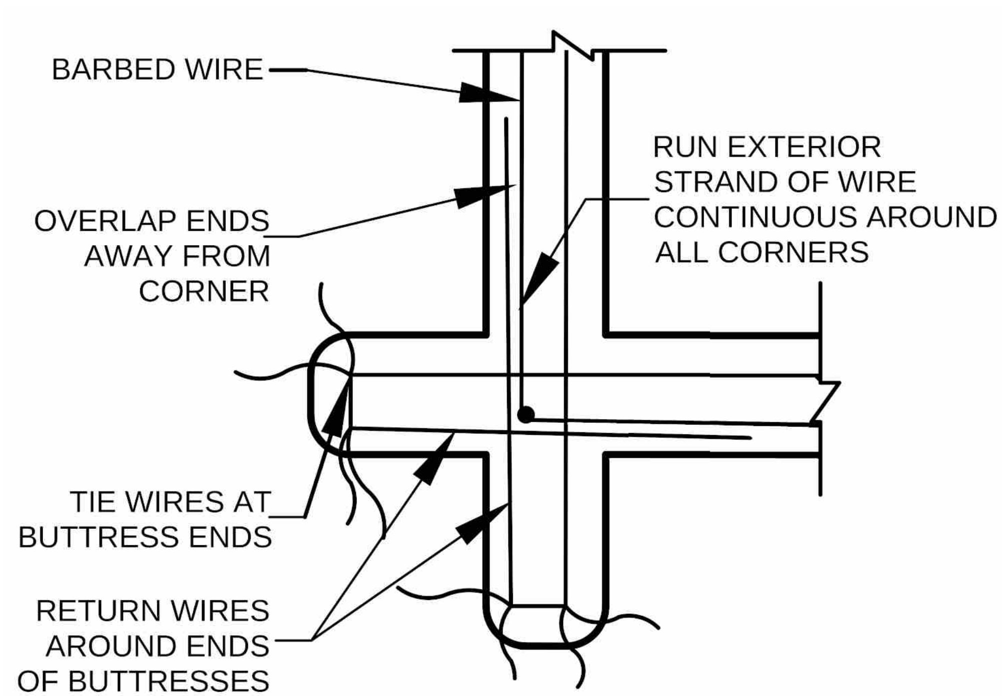

Figure 14: Unite corner buttresses fully to the walls by careful barbed wire placement.

A single buttress extending out one side of an external wall corner provides extra bracing in one direction and also protects cut-bag courses from mechanical damage (Figure 15). The vertical rebar must be either continuous from the footing or with the upper length set in place at half wall height. It can be connected to the lower rebar by pouring concrete over its bent end in an open splice (see section 6 for ways to splice separate rebars).

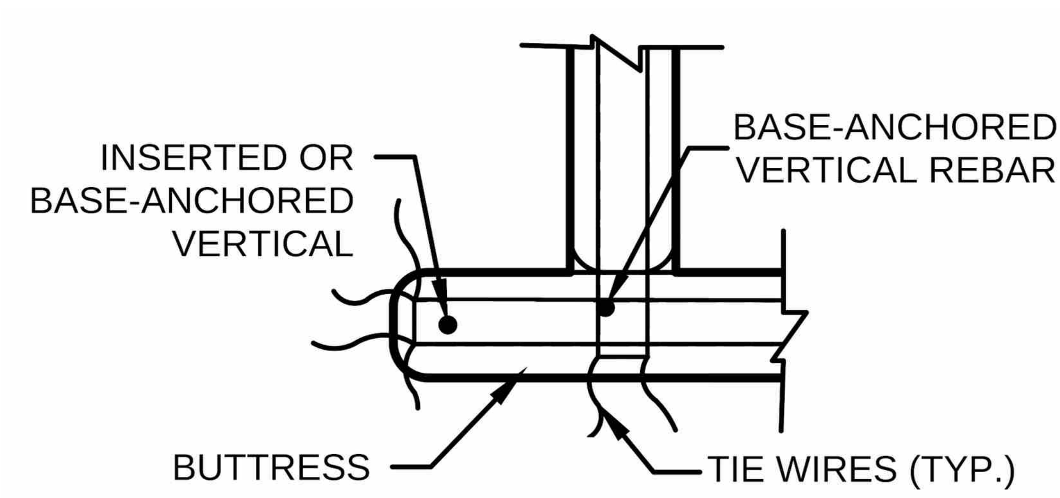

Figure 15: An exterior wall corner with only one buttress.

Always connect vertical rebars at corner locations strongly (or use continuous steel) so that stresses can be transmitted from the bond beam down through the wall all the way to the footing.

Less wall material is needed for a corner pier than for buttresses (Figure 16). No bracing capacity is added to the building to counteract force in a specific direction, but the extra material can add stability to reduce stress on the corner from generalized shaking.

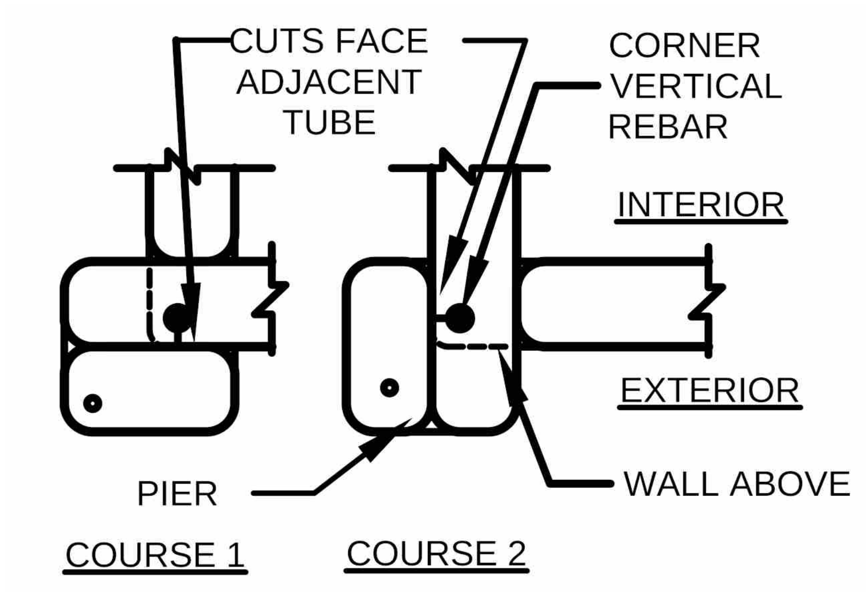

Figure 16: A corner pier shelters cuts to the container fabric.

Run the external strand of barbed wire continuous past a corner pier (Figure 17). Unite the pier to the wall with the internal strand of wire, and insert a rebar into pier courses.

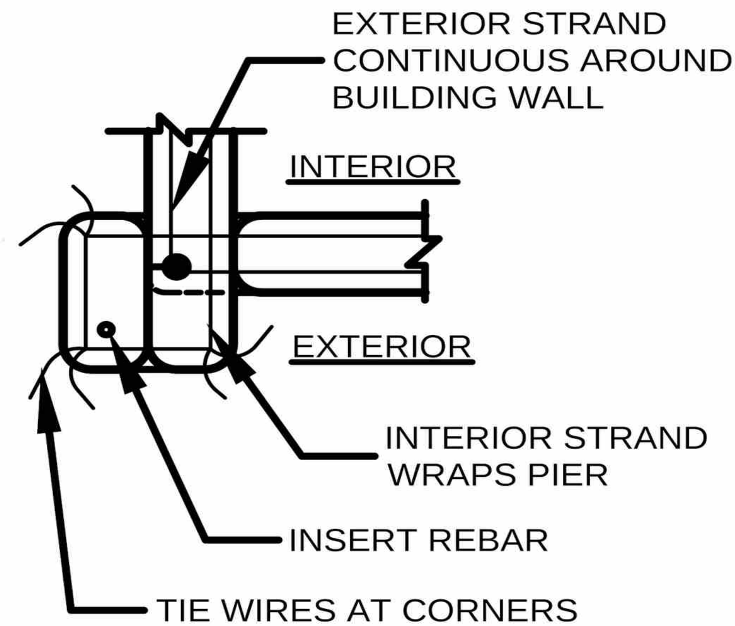

Figure 17: Run the interior strand of barbed wire around the pier and tie at corners.

A continuous vertical rebar, or a rebar joined to the lower segment with an open splice is needed with a full-height corner pier.

Gravel Bag Foundations and Base walls

Base walls can be built of gravel bag above the footing as a moisture break but need straps and pins to ensure gravel courses hold together well.

Strap all gravel courses vertically from beneath the main footing. Tie the strapping above one or two CE courses on top of the gravel courses. Never strap three or more courses of CE to avoid loose straps if the earthen fill shrinks during drying.

Angled Base Wall Pins in Gravel Bag

When using more than a single course of gravel bags above concrete also:

- Insert angled base wall pins through every bag or at least every 600 mm (24”)
- Bind barbed wire around straight segments of gravel bag interior wall footings

Insert rebar pins at a 30° or steeper angle down through at least two courses of contained earth. Start rebar pins 300 mm (12”) distant from footing pins and all other locations where longer rebars will be inserted above.

Binding Gravel Bag Courses

Barbed wire laid on gravel-filled courses does not attach strongly to the bags. Instead, run horizontal wire around bags (Figure 18a). Connect wire where strands end by inserting a small nail between the twisted wire of each strand. Lever it to pull the wires taut. Bend the nail and wrap it and the two wires with galvanized tie wire (Figure 18b).

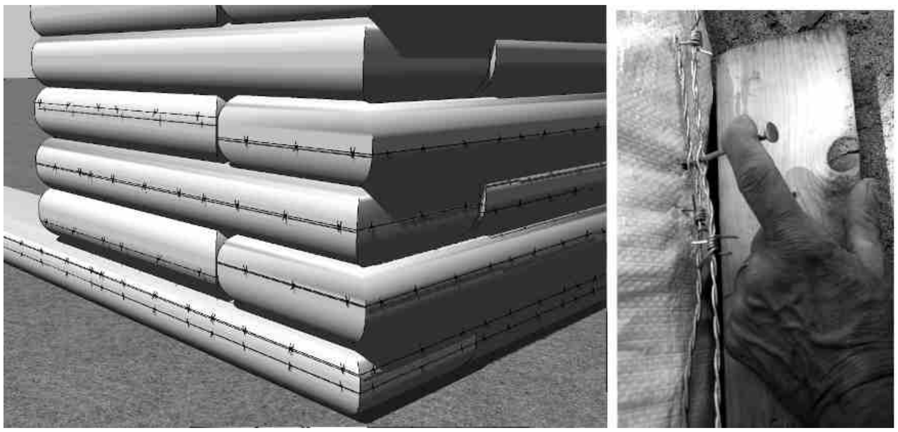

Figure 18 Bind gravel bag courses (left to right): a- wrap entire building below door sill then wrap around straight lengths of bags; b- Pull wire tight and fasten ends securely.

Or to join wire ends, twist loops around a rebar pin and embed it in a chunck of concrete.

Bind any straight lengths of gravel bag courses. On every course some buttress or stub wall sections cannot be bound (like the buttress on the top of Figure 19a). On the next course that element will have bags laid in the other direction (Figure 19b) and can be bound.

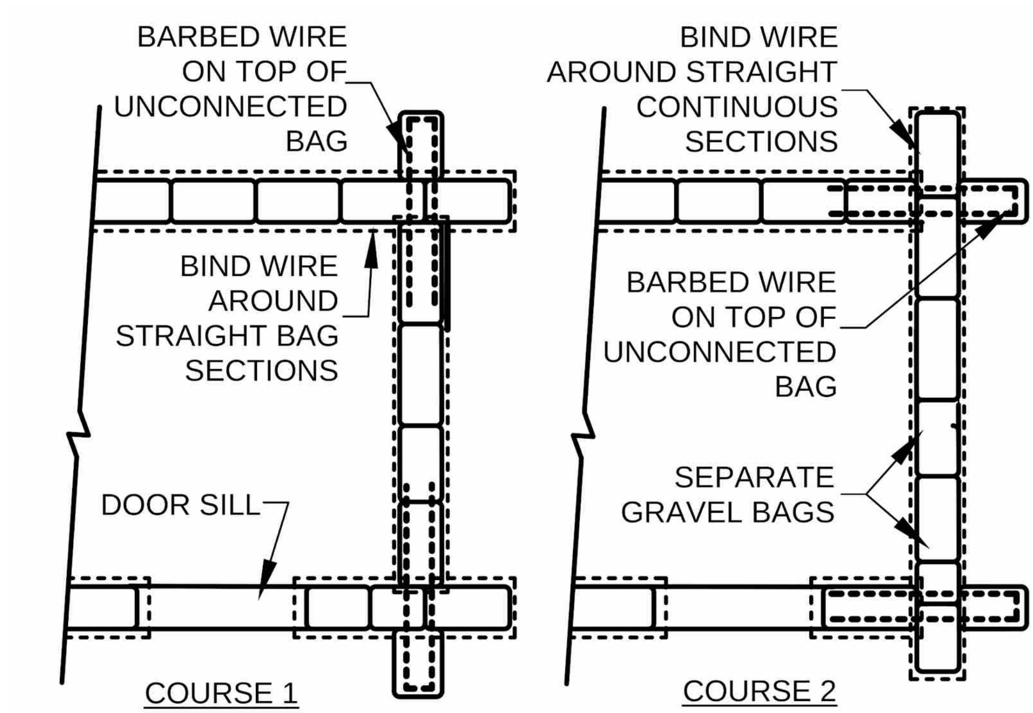

Figure 19 (right to left): a- Bind around straight lengths of gravel bag courses; b- On alternating courses bind the continous bag or tube lengths.

Embedding Rebar in CE Walls

Deformed (textured) rebar bonds well with wall fill material well when it is hammered into damp earthen walls. Steel rebar that is pre-anchored in a strong footing can also bond to soil when built using special techniques. Embed rebar either by 'punching' tubes and sliding them down onto a rebar (Figure 20a) or by cutting (Figure 20b) a small slice in a tube and fitting the course around the rebar.

Figure 20 Rebar in walls (left to right): a- Punch bags onto anchored rebar; b- Cut tubes to form around rebar.

Inserted Rebar Lengths

Although continuous or connected vertical rebars protect walls much better than separate inserted lengths, some unconnected rebar can be added as extra reinforcement to stiffen walls against out-of-plane forces.

Hammer rebars in accurately in the center of the wall width. Check for plumb with a level to avoid a long rebar hitting a barbed wire and bending to emerge from the wall below.

Next to openings insert rebar long enough to extend down into the courses beneath the opening. Rebar pieces as long as 2,1 m (7’) can be used although they flex when hammered in at this length. To insert rebars longer than 1,5 m (5’):

- Cut the tip at a sharp angle
- Prepare a guide hole by hammering a narrower smooth steel bar 300 mm (1’) deep in the correct location and then removing it
- 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 pull the tool down around the rebar to insert lengths of steel higher than they can reach
- Consider whether heavier diameter rebar may be helpful

Space Inserted Lap Rebars

Align separate pieces of inserted rebars one above the other at the location where reinforcement is needed. Use a separate shorter lap rebar that overlaps both the upper and lower verticals (Figure 21). The lap bar is parallel for only a short distance, but should be as far away from the main verticals as the length of the overlap.

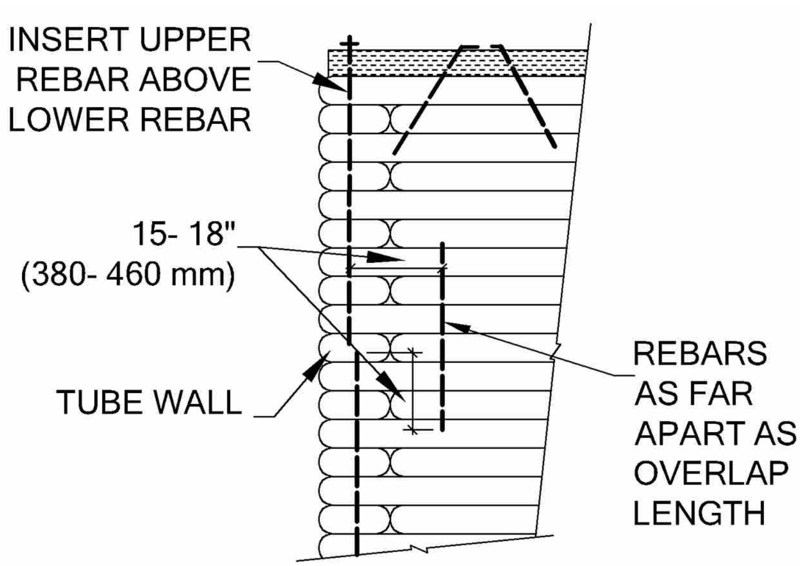

Figure 21: Align separate inserted rebar lengths where reinforcement is needed but use a shorter lap rebar spaced as far away as the overlap length.

Lap rebars are not needed if aligned separate inserted rebars are within 1 m (39") of a continuous vertical, a spliced vertical set, or other aligned verticals that break at a different course.

Diagonal Pins

Straight rebar lengths inserted at an angle lack stiff anchorage from a bottom hook but provide some resistance against upward forces as the steel bond to soil supports the weight of the fill.

Also use unconnected short diagonal rebars to connect elements together (door or window frames to walls, bond beams to walls, piers to main walls) where they can avoid hitting barbed wire on course tops.

When angled rebars are used aiming in different directions, insert them at least 100 mm (4") apart on top of the course.

VERTICAL REBAR CONNECTIONS

Rebars do not give maximum strength to walls unless the top stays connected to the bond beam. Use the correct end on any steel rebar in earthen walls.

HOOKS AT THE REBAR TOP

Where rebar will be embedded in concrete, use 255- 300 mm (10- 12”) long hooks bent on the end for major verticals at corners, wall intersections and near wall openings. Steel embedded in concrete should always have 25 mm (one inch) of cover or more.

A hook end can only be hammered to insert the rebar if it is bent at 90 degrees. Or bend the hook after inserting the rebar by attaching a heavy pipe wrench next to the earthen course and placing a long pipe over the end of the rebar about 75 mm (3”) above the wall.

Rebars inserted through wood lintels only need a short hook of 75- 100 mm (3- 4”). Because 12- 18 mm (half- ¾ inch) diameter rebar should not be bent in a radius tighter than 50 mm (2”), drill an angled hole next to the vertical hole for the pin. Let the curve near the hook sink into the wood so the hook is close on top of the lintel. Or instead of a bent hook, weld a perpendicular stub on rebars to be inserted through wood.

BOLTS AT THE REBAR TOP

If a base-anchored vertical rebar must be attached to a wood lintel or a steel window frame, weld a strong bolt to the end before anchoring it in the footing.

BASE-ANCHORED REBAR

Punched-bag or cut-bag techniques are equally useful on verticals at corners and wall intersections. For rebars in the middle of straight walls use punched-bag as much as possible with some cut-bag technique.

When tamping around vertical rebars already anchored in place, be careful to avoid cumulative creep. Maintain the rebar vertical at the correct distance from openings and/or wall surfaces.

PUNCHED-BAG CONSTRUCTION

Punched bags can be used wherever vertical rebar extend 1,2 m (4’) or less above the current wall surface. At corners it is natural to start the tube near the rebar that will be punched. Punched-bag holes used in the middle of a straight wall will require the start of another separate tube and will provide some disruption of the wall continuity.

For neat construction pre-measure and make a small cut near the stapled or sewn end of a tube (Figure 22a). 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 22b) and slide the rebar through the bottom and then the top hole (Figure 22c).

The fill will be loose when it has been slid down over the rebar. Reach inside the bag and re-firm or tamp the soil with a fist or wood piece. Continue to fill the tube and tamp after adjacent tubes are in place (Figure 22d).

Figure 22 Punched-bag construction (left to right): a- Prepared hole near tube end; b- Slide partly-filled tube end over a rebar; c- Locate and firm the tube end; d- No fabric gapping after filled and tamped.

At a corner the rebar should be 125 mm (5”) from the wall surface. But in the middle of a straight wall, start a new tube at least 150 mm (6”) away from the rebar location. Alternate sides to start the tube on the next course overlapped a good distance.

Punched tubes in the center of straight walls create extra ‘head-joints’ at the ends of the tube. Punched-bag tubes alternating around a rebar must also be built running in opposite directions.

The distances from the flat tube end and side must include enough fabric for the curving side and end of the tube.

Distance for hole from edge or end, laid flat	125 mm (5”) high courses	150 mm (6”) high courses
To be 125 mm (5”) from side	165 mm (6.5”)	178 mm (7”)
To be 150 mm (6”) from end	191 mm (7.5”)	204 mm (8”)

A tube that has been punched near the beginning can’t be punched again near the end. Punched-bag technique is usually combined with cut-bag technique to reduce head-joints.

Cut-bag Construction

Cut-bag technique embeds rebars anywhere in the length of a tube. Because rebars are needed near every wall opening or corner on high strength walls, the other end of a punched-bag tube usually needs a cut to embed a rebar.

Cut-bag did not reduce wall in-line strength in tests, even with cuts extending around half the container perimeter. But cuts and the wall material they expose are less vulnerable to mechanical damage when made at corners so they are located between adjacent tubes.

To use cut-bag, fill the tube end next to the rebar, letting it hang slightly over the edge of the wall on a metal 'slider' sheet so it doesn't stick to the barbed wire. When the course is full past the cut location, cut the bottom first then up to the top. Slide the tube into place with the fill surrounding the rebar. Pull the metal sheet out and settle the fabric on the barbs below. Place barbed wire, bending it around the vertical rebar if at a corner.

Like any resilient CE earthbag, cut-bag construction must be built with fill damp enough to solidify. Build the cut tube first, then place the tube next to it before tamping the first. If cuts are made in an exposed end or side of a wall, let an extra builder hold a board against the cut or tuck a square of extra fabric inside the cut before tamping to prevent a little soil loss.

When cuts are used near wall openings, alternate between the wall side and the wall end. Alternate cuts with punched bag to reduce both cut lengths and the number of head joints. For good overlaps between head joints and cuts, start punched-bag tubes at least 230 mm (9") from the rebar (Figure 23).

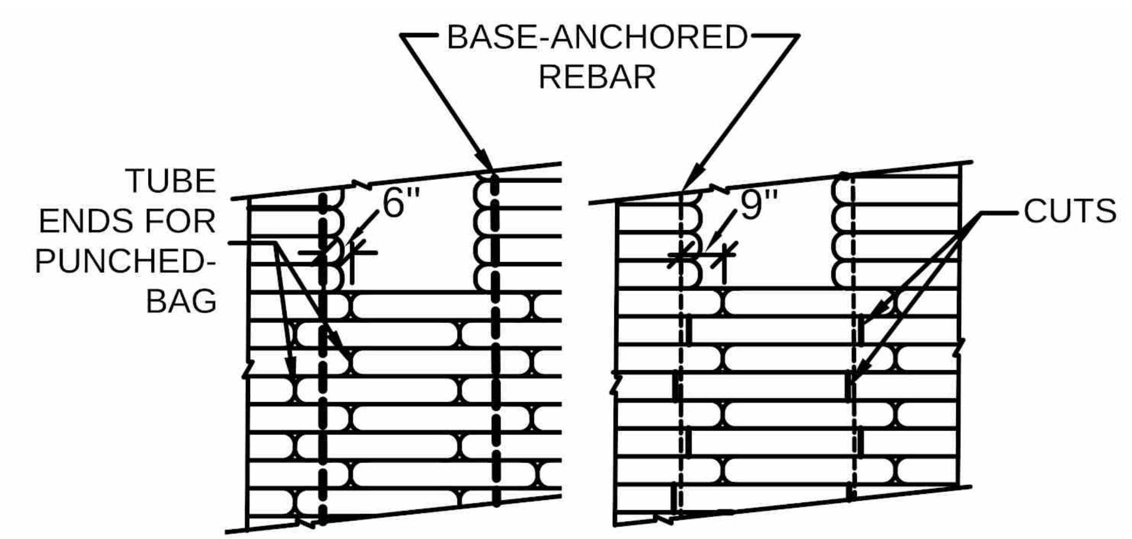

Figure 23: Head joints near rebar (left to right): a- for punched bag; b- where cut-bag techniques alternate with punched-bag.

6 INTERCONNECTED WALLS FOR MODERATE TO HIGH RISK

Steel reinforcement must form an interconnected 3D grid, with verticals connected by horizontals in the bond beam and footing.

> ***STRENGTH INCREASES MOST WHEN EMBEDDED REINFORCEMENT IS CONNECTED TO OTHER EMBEDDED REINFORCEMENT***

Use strong connections between steel rebars. Connection between rebars and soil is more important than connections between wire and rebar.

WALL INTERSECTIONS

At intersections of walls use embedded rebars to pin the alternating sections together. If there is no continuous vertical from a footing, insert spaced lap rebars in the center of the intersection so that the rebar pins the tubes and earthen fill from course to course.

On interior walls run barbed wire straight to where the wall ends. Do not bend barbed wire around base-anchored rebars in the crossing area of interior wall intersections.

EXTENDED WALLS, BUTTRESSES AND STUBS

Where interior walls end at the exterior wall they can continue into a buttress. Use the same width as walls, and run tubes continuous to the end of the buttress every other course. Insert lap rebars 200 mm (8”) from the end of the wall element to avoid barbed wire.

A buttress or stub wall must be at least 500 mm (20”) long but must not extend beyond walls more than 1,2 m (4’) maximum. Include full height buttresses and stub walls under the bond beam.

Build a stub wall or buttress longer than 1 m (39”) on a strip or full concrete footing and locate a continuous vertical rebar at the end.

CORNERS

Buildings with curved walls have innate bracing strength. A curve as small as 1 m (39”) in radius is stronger than a 90 degree building corner.

Rectangular buildings need reinforcement at corners. Use continuous vertical rebar at each exterior corner and embed the rebar fully in the damp soil fill.

Rebar pieces spliced together with a concrete plug act structurally very similar to continuous rebar, but allow fully three-dimensional connections between reinforcement.

Corner Buttresses

In high risk areas use two buttresses at each external wall corner to add bracing capacity.

Triangular Reinforcement in Special Locations

For at least one of each pair of corner buttresses, use stiff triangular connections between embedded steel reinforcement. Rectangular reinforcement grids rely on the strength of the connections to resist warping into a diamond shape. Triangular reinforcement webs are held at a specific angle by the bar lengths, and less vulnerable to deformation.

The simplest force triangle is a single brace made when a diagonal joins a vertical in a covered splice at mid-wall height. The triangle is completed when the vertical and diagonal are both embedded in the reinforced concrete bond beam with horizontal steel reinforcement.

Stronger reinforcement can result from doubled braces or rebar webbing shown in *B104 Extra Strength Resilient CE Details* available online at BuildSimple.org/ Resources.

Splices to Connect Embedded Rebars

Plan splice locations carefully because no rebar inserted from above can pass through a splice.

Open Splices

Concrete poured into an open space on top of a course makes an open splice which can connect vertical, diagonal and horizontal rebars inserted from the same course.

Build tubes at the splice layer to within 180 mm (7”) of the corner in one direction, and 300 mm (12”) in the other, tamping against a concrete block (Figure 24a). Leave an exposed gap large enough to include the hooks of the rebars. Insert rebars into the exposed gap (Figure 24b), locating a 255 mm (10”) long hook on each rebar passing through the splice. Adjust the rebar depth so the hook is no more than 75 mm (3") above the course top.

Pour concrete into the tube end to connect them. Shake it down into the tube well and tuck the end under (Figure 24c).

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.

Triangular doubled or truss-type braces need a horizontal that is inserted between two gaps for splicing. Have someone stand on a tamped section of course while another builder hammers the rebar through the center of the earthen fill.

Concrete in a splice does not need to be completely smooth on top, but lay barbed wire on immediately. Do not continue building above the splice until the concrete has hardened enough to survive tamping forces from above.

An open splice can also connect to the hook of a higher rebar. Support an upper rebar in place (Figure 25) with temporary bracing or tie it to a short vertical pin inserted next to it.

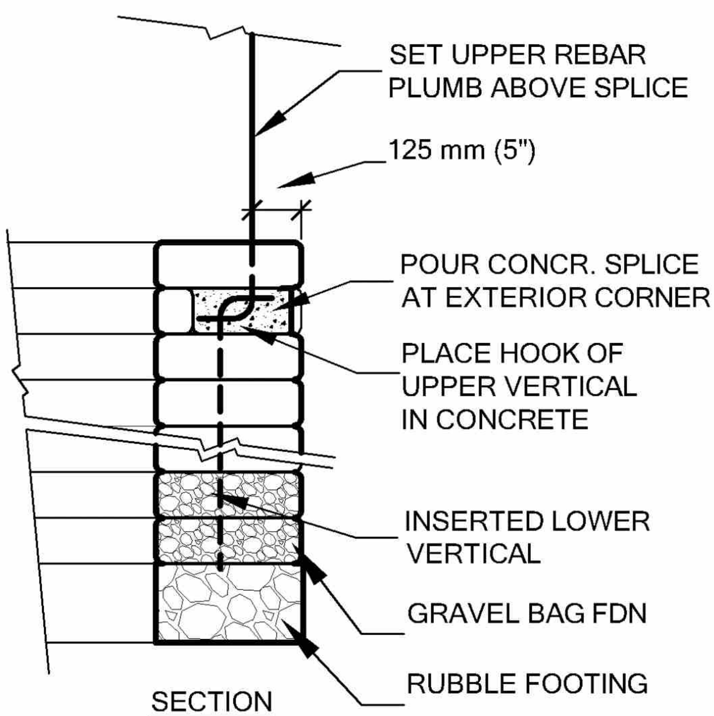

Figure 25: Open splice connecting upper to lower rebars.

At external corners the base-anchored rebar must be at least 100 mm (4”) away or further from the location for the upper rebar to allow both to be embedded in the concrete. The upper rebar must be 125 mm (5") from both sides of the outside surfaces of the walls.

Pour the concrete a full course deep and recheck the upper vertical for plumb. Or to avoid the need for long hooks on both rebars, leave a gap in the course above and pour the concrete two courses high.

Continue above the splice by punching tubes and sliding them down over the rebar.

Covered Splices

Covered or buried splices connect the bottom of rebars that are inserted from above. Locate them near a wall end, wall opening or the outside of a corner for access.

Locate a small target sandbag in a wall. Build above, then insert rebars down through the damp CE courses into the target bag. Cut the sandbag, remove the sand and fill the void space with concrete to connect the separate rebars.

A 150 mm (6”) wide area of concrete can connect rebars, but a splice sandbag at least 255 mm (10”) in diameter is easier to find with a rebar inserted from above. A splice at the end of a buttress, stub wall, or wall opening needs a sandbag as wide as the course.

Make covered splice sandbags two courses high because inserted verticals cannot have hooks on the bottom.

Strong mesh in the space can guide concrete into the back of the void to embed the whole length of the rebars. A hard form is needed at least half the height of the gap so that even a relatively dry mix of cement won’t flow out of the space.

Steps to Make a Covered Splice

1 PREPARE: Build the wall to the bottom of the splice with a vertical rebar extending 200 mm (8”) above. Sew or staple a 510 mm (20”) long tube into a flat width 195 mm (7.75”).

2 PLACE MESH: Place piece or tube of mesh at least 510 mm (20”) long on the rebar.

3 PLACE THE SANDBAG: Partly fill the 255 mm (10”) diameter upright fabric sandbag. Cut a hole and lower the bag onto the lower rebar (Figure 26a) into or onto the mesh. Fill with sand and close around the emerging lower bar.

4 CONTINUE THE WALL: Fill courses next to the sandbag. Insert cut ends of barbed wire through the mesh bag (Figure 26b). Build above the sandbag (Figure 26c).

Figure 26 Covered splice preparation (left to right): a- target sandbag inserted over rebar into mesh tube; b- courses laid next to the sandbag; c- courses added above the sandbag.

5 INSERT THE UPPER REBAR down to pierce the sandbag. Let the wall dry one to two days.

6 PREPARE THE SPLICE GAP: Cut the sandbag, remove sand and/ or fabric. Bend all exposed barbed wire into the gap space (Figure 27a). Tack a form in place.

7 ADD CONCRETE TO THE SPLICE: Pour concrete into the mesh bag. Squeeze mesh to place concrete around the rebar (Figure 27b). Trim excess mesh and remove the form (Figure 27c). Leave surface rough so nook plaster to level the surface will adhere.

Figure 27 Casting a covered splice (left to right): a- Remove sand and sandbag fabric, b- Place form and use mesh to fill the top, c- Concrete splice with mesh trimmed.

Diagonal Wall Reinforcement

Using a connected diagonal brace on at least one side of each external wall corner will add some stiffness to the wall tops where forces are highest during an earthquake. The diagonal brace can occur in either a buttress or in the wall next to a corner or next to a door opening.

Draw a side wall view to be sure that diagonals are long enough for their location (Figure 28). Or use these dimensions with a rebar inserted at a 60 degree angle:

Diagonal rebar length	Distance wall top to bottom of target sandbag	Distance from splice to insertion point
1,5 m (5')	1,2 m (4')	660 mm (26")
1,8 m (6')	1,37 m (54")	760 mm (30")
2,1 m (7')	1,5 m (5')	860 mm (34")

Wherever a covered splice occurs the vertical does not have to be a continuous full-height rebar. Instead it can be spliced to reduce tube cutting.

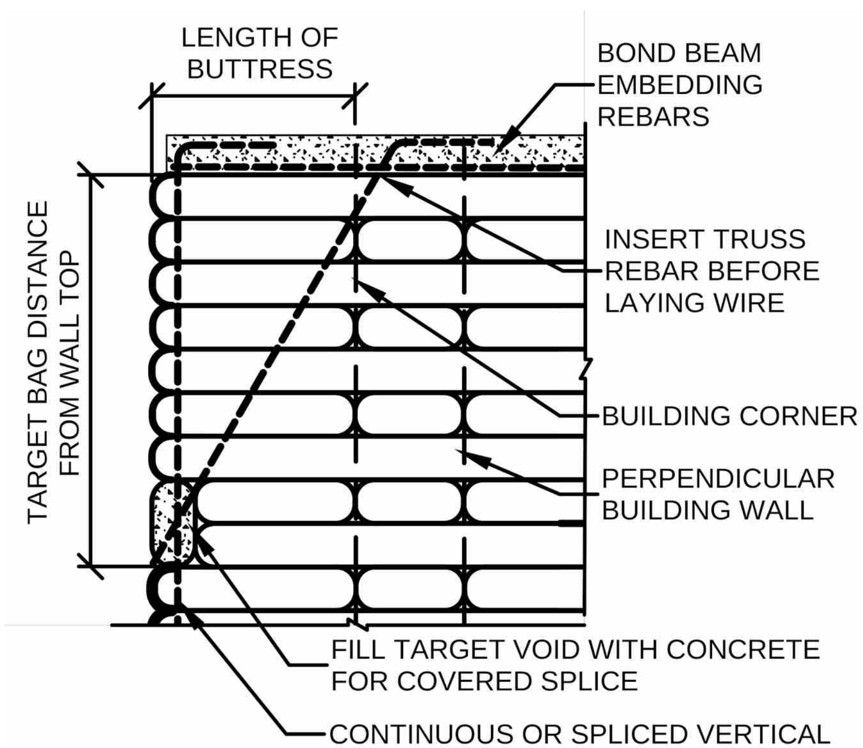

Figure 28: Choose lengths of connected diagonals to end in a covered splice.

Insert diagonals into splice target bags carefully. Use guide poles next to the wall or attach a tag to the outside of the target bag so that builders can aim the rebar accurately at the splice bag.

Diagonals starting at a wall corner and extendinginto a buttress could conflict with the external wall strand of barbed wire unless the diagonal is inserted before laying barbed wire on the top course.

Braces can also be used at any point in a wall next to a corner or wall opening, with the covered splice at the door or window opening.

7 WALL OPENINGS FOR MODERATE TO HIGH RISK

Courses above openings benefit from extra connections to bond beams and nearby wall material. Walls next to openings benefit from extra reinforcement because forces from the entire length of wall are concentrated between openings.

Lintels over openings 1- 1,5 m (3' -5') wide need pins on top to unite to the courses above. Use at least two 150 mm (6") long vertical pins near the center of the opening. As the earthbag course above is filled, lift it and settle it onto these short pins.

LINTELS

Lintel size and strength should relate to the span length and weight of wall above the opening and extend 300 mm (12") or more each side of an opening.

Wood lintels allow the use of upward pins, but if narrower than 255 mm (10") must be placed on a 250 x 50 mm (2 x 10) bearing plate to spread weight carried by the lintel out across more of the wall thickness.

Lintels can be sized according to New Zealand's earth building guidelines if heavy earthen walls extend 1 m (39") above the lintel:

WIDTH OF OPENING	SIZE OF WOOD LINTEL	TYPE OF LINTEL
≤900 mm (35")	100 x 300 mm (4 x 12) laid flat	single piece of wood
	three 100 x 100 mm (4 x 4)	built-up
≤1,5 m (5')	150 x 300 mm (6 x 12) laid flat	single piece of wood
	three 150 x 100 mm (4 x 6)	built-up

Use standard masonry guidelines when there are fewer earthbag courses above lintels.

CONNECT LINTELS TO THE BOND BEAM

Vertical spliced or continuous rebars near wall openings should also pass through holes in lintels (Figure 29). Slide the lintel down over the verticals. Continue building courses above the lintel. Punch or cut courses at the verticals above the window. Bend the hook on the vertical just before pouring the bond beam.

Vertical rebars near wall openings must pass through lintels. Drill holes near the ends of all wooden lintels where the base-anchored vertical rebars are located, approximately 125 mm (5”) beyond the edge of the window or door. At minimum, insert vertical lap rebars hrough lintels.

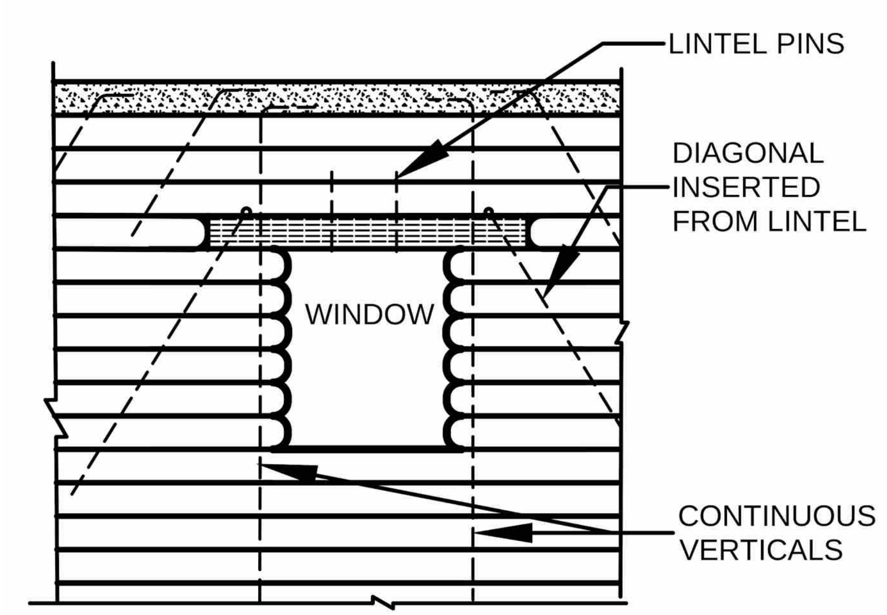

Figure 29: Long diagonals from lintels can stiffen vulnerable parts of walls.

CONNECT LINTELS TO WALLS NEXT TO OPENINGS

On buildings with more than the minimum space between wall openings, also insert diagonal rebars downward through wood lintels (Figure 29). If possible, extend them into courses below the window opening.

Drill holes for diagonals through lintels in the center of the wall, so that holes for the vertical rebar are at least 4” from the diagonal hole tops.

8 BOND BEAMS FOR MODERATE TO HIGH RISK

Connections to the wall and to the roof above must be stronger than many builders expect because earthquakes exert the highest forces on wall tops. A bond beam must have enough steel to resist horizontal stresses that include the weight of the wall and roof or loft. Consider the wall thickness and height, the type of roof and/ or loft and the distance between bracing lines when choosing reinforcement.

Check with local engineers before using traditional construction. In areas subject to strong winds use special attachments for roof beams that are embedded in the bond beam.

Concrete Bond Beams

Because plaster is an important part of the reinforcing system of resilient CE earthbag, attach the plaster mesh strongly at the wall top. Embed mesh in concrete bond beams.

The bond beam concrete must embed tops of all pins as well as bent hooks on vertical rebars. Insert steel so hooks are contained within the depth and width of the bond beam.

Guidelines in New Zealand recommend bond beams 75% as wide as the wall. Earthbag courses built 125 mm (5”) high have a flat top surface 67% the width of the completed wall. Builders can side tamp the top course of a resilient CE wall while course edges are still damp to flatten the curved outer surface and allow a slightly wider bond beam to rest on the wall top. When side tamping have at least one person stand on the course.

Insert diagonal pins joining wall tops with bond beams while wall material is damp. Space pins that extend 600 mm (24”) deep into the wall 600 mm (24”) apart on average at alternating angles. Conventional earthbag relies on the alternating angles of these pins to hold the bond beam to the wall. Because resilient CE relies on bolts or strong hooks on the vertical rebar, angled pins are not the only connection to bond beams but may provide wall stiffening as well as fine grained connection between bond beam and wall.

Steel Reinforcement

In high seismic risk areas 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.

Bracing wall distances 90% of the New Zealand recommendations for adobe or rammed earth with a conventional light roof are:

Bond beam size	Rebar size	Max. bracing distance
285 x 150 mm (6” x 11.2”)	Two D16 (5/8 inch)	3,8 m (12’- 6”)
285 x 175 mm (7” x 11.2”)	Two D20 (0.9 inch)	5,1 m (16’- 9”)

For buildings with a heavy roof the bracing distances for the same size bond beams are reduced to 3,2 m (10’- 6”) or 4,6 m (15’- 1”) respectively.

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 where both vertical rebar and also angled pins can be welded or bolted to it.

Because a steel tube bond beam 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. Tie plaster mesh to the strapping.

Extra-strength soil fill or stronger stabilized fill is recommended for the top course under a welded steel bond beam because roof weight will be more concentrated.

9 ABBREVIATIONS AND DEFINITIONS

BRACE	Assembly of separate rebars embedded in earthen wall material joined with concrete splices to form at least one force triangle when united to the steel in the bond beam
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
REBAR TRUSS	Assembly of separate rebars embedded in earthen wall material joined with concrete splices to form three or four force triangles
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