Structural Assessment and Retrofit Design of Old Unreinforced Masonry Buildings in the U.S.

Course No: S04-027
Credit: 4 PDH

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1. Chapter 1: Introduction to URM Structures in the United States

1.1 Historical Background and Prevalence

Unreinforced masonry—URM if you're cool with acronyms—pretty much built the backbone of old-school America. Before concrete and steel strutted onto the scene, folks slapped up brick walls everywhere. Seriously, you name it: schools, courthouses, firehouses, warehouses, churches, even those slightly spooky old apartment buildings. If you've ever wandered through a downtown that looks like it belongs in a sepia photo, odds are you've brushed past a URM building.

Back in the late 1800s through the early '40s, these things were popping up all over. Brick and lime? Dirt cheap and everywhere. Construction? Straightforward. Labor? Also cheap. So, URM was basically the obvious move, especially in cities where everything had to go up fast and on a budget.

And here's the kicker—these buildings are still hanging around all over the place. The Northeast? Packed with 'em. Midwest and the West Coast? Same deal. Some are pristine, some are… well, let's call it "charmingly crumbling." Either way, they're part of the local DNA at this point.

You'll spot URM buildings in:

- Old town squares and civic hotspots
- Pre-1950s school campuses (think: Hogwarts, but with more asbestos)
- Brick warehouse districts
- Military bases and train stations
- Churches and those classic mission-style buildings, especially down Southwest way

1.2 What Makes URM Structures Tick (Or, Not Tick)

Here's where the engineering nerds perk up. URM buildings are kinda wild—no modern bells and whistles. We're talking solid brick walls (sometimes hollow, but not in a fun way), stuck together with lime or weak cement. Floors and roofs? Usually wood joists or steel beams just jammed into the walls—no fancy anchors, nothing holding them tight if things start shaking.

And get this: there's zero steel inside the walls. Nada. So, when you hit 'em with sideways force (like, say, an earthquake), the walls just… snap. No flexibility, no give. That's why they're legendary for falling apart when the earth moves.

Diaphragms? If you see a rigid one in a URM school, buy a lottery ticket—it's rare. Mostly, you get flexible wood, which is code for "not great in a quake."

Other quirks:

- Super brittle—once things start to go, it's curtains
- The walls behave differently depending on which way the force hits them (engineers call this "orthotropic," but you don't have to)
- No real effort was made to tie walls and floors together, so the whole thing is structurally… eh, let's say "vulnerable" and leave it at that

1.3 Building Codes and Earthquake Epiphanies

People used to think these old brick beasts were totally solid—until 1933, when the Long Beach quake hit and basically said, "Guess again." After that, the West Coast got serious about updating building codes. Did every URM building get fixed up? Ha, not even close. Tons of them are still standing, untouched, hoping the next big shake skips their block.

Seismic codes started showing up for real in the '70s, but most states didn't force owners to retrofit old buildings. A few places—California, Utah, Oregon, Washington—put their foot down, but for most of the country, it's still "retrofit if you feel like it." Not exactly reassuring.

Lately, there's been a bit more awareness. School districts, city planners, and history buffs have started paying attention. You've got FEMA doing risk checks, California pushing for retrofits, ASCE 41 giving engineers some guidelines… but honestly, unless there's a law with teeth, a lot of these buildings are just crossing their fingers and hoping for the best.

1.4 Types of Cracks and Structural Deterioration You'll Actually See

URM buildings get old just like the rest of us, and you don't have to look too hard to spot the scars. Here's what usually pops up:

- Diagonal cracks running away from windows and doors. These bad boys usually point to quakes or the building settling in weird ways. Not cute.
- Walls that bulge or bow out, especially up top or at parapets—like the building's got a beer belly. Always makes you nervous walking underneath, right?
- Mortar joints cracking along the lines, thanks to crappy bonding or the building expanding and shrinking with the weather. (Bricks and mortar are dramatic like that.)
- Mortar turning to dust or bricks looking chewed up from water sneaking in over the years.
- Layers of thick walls starting to peel apart, or you see gaps where the walls aren't tied together—looks sketchy, and, honestly, it is.

Honestly, if you don't know these signs, you're just guessing what's wrong. Spotting them is step one before you even think about fixing stuff. We'll get into the "how to" later, promise.

1.5 The Engineering Imperative

Here's the deal: URM buildings are like that old classic car—gorgeous, but you wouldn't trust it on the freeway. We love them for history, but let's be real, they're kinda a nightmare when it comes to safety.

Fixing these things isn't just about slapping on some new bricks and calling it a day. Engineers have to walk a tightrope: keep people safe, keep the building legal, don't blow the budget, and—oh yeah—don't ruin what made the place cool in the first place.

This whole course? It's built on that juggling act. As engineers, you're supposed to:

- Actually, know what you're looking at—history, structure, all that jazz.
- Use up-to-date standards (like ASCE 41-23, if you're into that sort of thing) to figure out what the old gal can handle.
- Suggest fixes that work, won't break the bank, and don't trash the original character.
- Be able to defend your choices—why you did what you did—with solid logic and paperwork that won't get laughed out of a review meeting.

2. Chapter 2: Methodology for Structural Assessment of URM Buildings

Alright, let's be real—checking out old unreinforced masonry (URM) buildings isn't just about poking around at crumbling bricks. First off, you gotta get a feel for what shape the thing's actually in, but you also need to dig into how people slapped it together in the first place. Spoiler: these aren't modern glass-and-steel skyscrapers. Most of the time, there's basically zero paper trail, no fancy rebar hiding in the walls, and half the construction choices make you go, "Wait, they did what?"

So, you're not just playing engineer—you're part detective, maybe even a bit of an archaeologist. You've got to snoop around, run some tests, figure out if the materials are still doing their thing, and try to piece together how all the parts interact (or don't). Usually, you're looking at four main steps: a quick once-over, poking and prodding the materials, digging into the structure itself, and then seeing how everything works together. It's messy, but honestly, that's half the fun.

2.1 Preliminary Survey and Visual Inspection

Alright, so, step one—yeah, the biggie—when you're sizing up some ancient, battered brick building with zero rebar holding it together? You gotta start with a good old-fashioned look-around. And I don't mean just strolling through, snapping a few pics for Instagram. We're talking a hands-on, eyes-wide-open hunt for trouble. You need sharp instincts, a half-decent knowledge of how folks used to slap these things together, and a knack for spotting weird stuff others might miss. Basically, channel your inner building detective. Purpose of the Visual Inspection.

The purpose of this inspection is to develop a comprehensive understanding of the building's current physical condition, identify visible signs of structural distress, and begin forming hypotheses about how the structure behaves under gravity and lateral loads. It also helps the engineer prioritize areas for detailed testing and modeling, ensuring that time and resources are used efficiently.

What to Look For

Alright, let's cut through the boring checklist vibe and talk real. When you're eyeballing a URM (unreinforced masonry, for those not living in a codebook) building, here's what actually matters:

- Crack Patterns

Cracks in brickwork? They're like the building's diary entries, and yeah, they're dramatic. Vertical cracks—think of these as the building slumping or shrinking. Diagonal cracks, especially around the corners or windows, usually scream, "Hey, we just got rocked by an earthquake or some gnarly wind!" Horizontal cracks near the floors or up by the parapet? That's more like the walls trying to bust out because they're not anchored down right. Each crack's got its own little horror story.

- Bulging or Out-of-Plane Weirdness

If the wall's starting to bow out, even by a hair, that's no joke. It's a neon sign flashing: "We're losing it!" Could be the bricks aren't sticking together anymore, or maybe water's gotten in and frozen, busting things up. Either way, if there's an earthquake, that's the spot you do not want to be standing near.

- Wall Separation

If you spot walls pulling away from the floors or the roof—yeah, that's a bad time. Old buildings? They usually skipped the whole 'anchoring' thing. So when stuff starts shaking, those floors are basically just along for the ride.

- Mortar Condition

Mortar's like the glue holding your Lego castle together. If it's turning into dust or crumbling when you poke it (and yes, you should poke it), the wall's losing its mojo. Don't trust it to hold up under pressure.

- Parapets and Chimneys

These are the first to peace out in an earthquake. Wobbly bricks, cracked tops, or chimneys that just look sketchy? Pay attention—these bits are notorious for collapsing when you least want them to.

- Moisture and Funk

Water's the silent killer here. White salty stains (efflorescence), weird green patches, mold—if you see any of that, especially around busted gutters or missing flashing, you've got problems. Rot and brick don't mix.

- Old Repairs or Dodgy Fixes

Spot any weird patches, obvious steel bolted into the wall, or sections that look like they've been Frankensteined back together? Sometimes, repairs hide more issues than they fix. Don't just trust the facelift.

- Roof and Floor Connections

Take a gander at how the floors and the roof meet the walls. Notice any beefy anchors or plates? Or is the floor sagging like a teenager's jeans in the '90s? If there's no visible connection, or it looks overloaded, that's a weak point just waiting to fail.

Bottom line: URM buildings aren't subtle about their problems. They leave clues everywhere—cracks, bulges, weird stains. Just got to know where to look and not get fooled by a fresh coat of paint.

Tools and Techniques

Honestly, nothing beats a seasoned engineer's eyeballs—those folks can spot trouble like nobody's business. Still, there's a whole toolbox of gadgets that make the job easier (and save a few knees and necks):

- Plumb bobs and those fancy laser levels? They're clutch for catching walls that are doing their best Leaning Tower of Pisa impression.
- Measuring tape and crack gauges—oh yeah, gotta get nerdy about those cracks. How wide? How long? Patterns? Snap a pic or jot it down, otherwise you'll forget by lunch.
- Drones aren't just for YouTubers—toss one up to peek at sketchy chimneys or roof bits you'd break your neck trying to reach.
- Your phone's camera (or some annotation app, if you're feeling high-tech) is perfect for grabbing quick shots and scribbling notes before you forget what you even looked at.

And hey, if you can dig up old blueprints or plans, you're halfway to detective status. Overlay your damage notes right on those drawings. No plans? No problem. Most engineers end up sketching floor plans on paper napkins or whatever's handy, marking where stuff's going wrong. Not exactly fine art, but it gets the point across.

Documentation and Interpretation

Every observation should be recorded with both a **narrative description** and **visual reference**—ideally color-coded on annotated floor plans and elevation diagrams. Cracks are typically ranked by width and activity (e.g., active vs. stable). Wall conditions can be scored or labeled (e.g., "severely deteriorated," "moderately cracked," "no visible distress") to inform later engineering judgment.

The goal is to **develop a working model in the engineer's mind**: How is this building carrying its loads? Where are the vulnerabilities? What would happen during an earthquake?
This is the point where engineering experience becomes invaluable. A seasoned engineer can often infer the likely load path and failure mechanisms based solely on visible signs. Still, no final decisions are made at this stage—it's about developing an informed plan for testing and modeling.

You can review the Field Inspection Checklist for URM Buildings in Appendix A at the end of the course.

2.2 In-Situ Material Testing and Investigation

Alright, picture this: you've finished walking around the old building, clipboard in hand, jotting down all those weird cracks and suspicious lumps in the walls. Cool. But now comes the real fun—time to roll up your sleeves and see what's actually going on inside the walls, not just what's peeking out at you.

Honestly, with ancient unreinforced brick buildings, you can forget about finding neat blueprints or tidy records. Half the time, you're lucky if you get a coffee-stained sketch. So yeah, poking around with in-situ tests isn't just a nice-to-have—it's survival mode for anyone who wants to figure out if the place will stay standing.

Here's the deal: these buildings are basically patchwork quilts stitched together by different crews over decades, sometimes centuries. What looks like a solid brick wall? Could be hiding all sorts of nonsense—random materials, crumbly mortar, empty gaps, or who knows, maybe even some forgotten bootlegger's stash. Making wild guesses is a surefire way to end up on the evening news for the wrong reasons. That's why these tests matter.

Out in the field, you'll see engineers busting out all sorts of gadgets. One of the classics is the flat-jack test. Sounds fancy, but the idea's simple: cut a little slot in the mortar, slide in a pancake-shaped jack, and pump it up. You watch how much pressure it takes to nudge the wall back to where it started. That number? Tells you how stressed out (literally) the bricks are and how much flex they'll give before things get dicey. Super handy when a wall looks fine but might actually be one bad day away from giving up, especially if someone messed with it in the past or the load isn't spread out right.

So yeah, don't trust a pretty brick face; dig in, test it, and get the truth.

Alright, let's ditch the stiff lab-coat language and talk straight.

So, around the building, you've got these pretty basic but surprisingly handy tools for checking how tough the bricks and mortar really are. Ever seen a Schmidt hammer? Looks like something you'd use to smash open a lobster, but it's actually for bouncing off walls—literally. You smack the surface, see how much it bounces back, and boom, you've got a ballpark idea of the compressive strength. It is not rocket science, but it does the trick.

Penetrometers are another story. You shove a needle in with a set force and see how far it goes. The deeper it dives, the softer your mortar. It's a quick way to see if one wall's a marshmallow while another's built like a tank. Both tools are like the building's personal trainers, finding weak spots or half-baked repairs that look fine until you poke them.

But honestly, if you want to get the real dirt (literally), you've gotta core sample. It's invasive—think of it as taking a biopsy of the wall. Drill out a chunk, send it to the lab, and suddenly you know how strong it really is, how well the bricks and mortar are holding hands, and whether there's any funny business hidden inside. Of course, picking where to drill isn't just eeny-meeny-miney-mo, especially if the place is historic and every brick has its own fan club. When you're done, you gotta patch it up so no one notices the "surgery scar."

Let's not forget about moisture, which is basically the silent killer of old masonry. Moisture meters? Yeah, they're the ghostbusters for damp walls. You check near the base, the roof, all those weird corners—if there's water lurking, these things will find it. And if you spot salts hanging around (not the table kind—think nasty stuff like sulfates and chlorides), you've got trouble brewing: salt crystals expand inside the brick, push it apart, and before you know it, you've got a crumbling mess. Catch it early or pay the price later.

Then you've got anchorage tests—kind of like a strongman competition for bolts. You stick a rod or anchor in, yank on it, and see if the wall says "no problem" or just gives up. If you're planning to bolt on new reinforcements or tie things together for earthquakes, you need to know if the wall's up for it. No sense retrofitting if things are just going to rip out.

Put it all together, and you're basically piecing together the building's medical chart. These tests tell you if you can trust the walls to do their job, where you need to beef things up, and what kind of repairs you can get away with. Skip this step, and you're just guessing—dangerous in this game.

But, you know, numbers only take you so far. You've gotta read between the lines. Maybe a wall only clocks in at 3 MPa on the compression test, but if it's not holding up much and everything's tied together nicely, it might be fine. Meanwhile, a wall flexing at 7 MPa could be a disaster if the mortar's falling out or it's wobbling sideways. That's when experience kicks in—no test replaces a seasoned engineer's gut feeling.

End of the day, all this in-situ testing? It's how you see past the surface. It's how you respect what's old, figure out what's really going on, and make the right call to keep people (and history) safe. Yeah, it's technical, but it's way more than just numbers on a page—it's about doing the job right.

2.3 Structural Evaluation and Capacity Checks

Looking past the obvious cracks: Building real trust with some old-school engineering smarts.

So, you've poked around the building, spotted the gnarly cracks, maybe tapped a few bricks, and run those in-situ tests to figure out what this old masonry's made of. Cool. Now comes the real test—figuring out if this thing can actually stand up to the kind of forces it'd see in the real world, or, you know, during the Big One. This is where you stop playing detective and start playing doctor—actually diagnosing what the structure can handle and what's likely to make it cry uncle.

Here's the curveball: With ancient unreinforced masonry (URM), you're not exactly blessed with crystal-clear blueprints or some Instagram-perfect rebar layout. Nah, you're working with half the info, a healthy dose of guesswork, and whatever gut instinct the years have given you. Honestly, it's part science, part art... with a smidge of anxiety thrown in.

Let's talk in-plane shear—basically, how the wall tries not to go sliding sideways when the ground starts dancing. Unlike those fancy reinforced concrete walls, old-school bricks rely on friction, some sticky mortar, and the way the bricks snuggle together. Problem is, that system only works until cracks, water damage, or a century of settling start picking it apart.

Usually, the engineer chops up the wall into chunks, or "piers," using windows, doors, or whatever's in the way as boundaries. Each pier acts like a mini-barricade, fighting to keep the roof or floor from shoving it around. It's not a perfect science, but hey—neither is working with buildings older than your grandma.

The **nominal shear strength** (τ) of a masonry wall can be estimated using simplified mechanics:

$$\tau_n = \frac{V}{t \cdot l}$$

Where:

- V is the applied shear force on the wall segment,
- t is the wall thickness,
- l is the effective length of the pier.

To assess adequacy, this nominal shear stress is compared with allowable shear values from ASCE 41 or ACI 530, adjusted for in-situ conditions. For URM, allowable in-plane shear strength might range from **0.06 to 0.1 MPa** in deteriorated lime mortar walls, increasing slightly if grouting or stitching has been used previously.

If the observed crack patterns align diagonally or show stair-step progression through mortar and brick, it indicates that the pier has likely already exceeded its in-plane shear capacity at some point in the past. Such damage warrants a reduction factor or safety margin in the design check.

Out-of-Plane Flexural Capacity: The Tipping Risk

Next comes **out-of-plane evaluation**, which is often the more dangerous failure mode. URM walls that are not properly braced can collapse outward during seismic shaking or high wind loads. This behavior is especially prevalent in parapets, gable walls, and tall unbraced sections. Engineers evaluate this risk by first calculating the wall's **slenderness ratio**:

$$SR = \frac{h}{t}$$

Where:

- h is the unsupported height of the wall,
- t is the thickness.

Walls with an $SR > 10$ are considered vulnerable and may not meet basic out-of-plane bending capacity without support. The wall is then analyzed as a simply supported or pinned plate subjected to lateral loads (typically seismic acceleration or wind pressure). The goal is to

estimate the **moment demand** (M) and compare it to the **moment capacity** (M_n) of the unreinforced wall section.
In a simplified case:

$$M_n = f_t \cdot S$$

Where:

- f_t is the flexural tensile strength of the masonry (often governed by mortar bond),
- S is the section modulus (b × h² / 6).

Because unreinforced masonry is weak in tension, these values are typically very low. In most cases, the wall's out-of-plane strength is insufficient unless retrofitted—either by anchoring to a diaphragm, adding center core reinforcement, or providing shotcrete or FRP overlays.

Capacity-to-Demand Ratios (CDRs): The Engineer's Dashboard

A practical way to summarize structural adequacy is by calculating **Capacity-to-Demand Ratios (CDRs)** for each wall element and failure mode. A CDR less than 1.0 indicates deficiency, while a ratio above 1.0 shows that the wall can withstand the expected forces with a safety margin.
CDR=Nominal Capacity / Applied Demand

For example:

- If a pier has a shear capacity of 50 kN and is subjected to a seismic shear of 60 kN, then: CDR=50/60=0.83, which indicates a **deficiency**.
- Similarly, if the flexural capacity of a wall under out-of-plane loading is 2.4 kNm and the demand is 1.6 kNm, then:
  CDR=2.4/1.6=1.5, showing **adequacy** with a 50% reserve.

These ratios guide retrofit priorities: walls with CDRs below 0.85 may need strengthening, anchorage, or bracing depending on the governing mode of failure.

Beyond Single Elements: The Structural System

An equally important part of the evaluation is how **walls interact with diaphragms and each other**. A perfectly adequate pier may still fail in real life if the floor diaphragm doesn't transfer load properly, or if it separates under seismic shaking. Engineers must evaluate:

- How walls are tied to floors and roofs
- Whether lateral load paths are continuous
- If torsion or load concentration is causing localized overstress

This part of the evaluation is best conducted using software such as **ETABS**, where wall stiffness, floor flexibility, and gravity loads can be assembled into a holistic model. But even before modeling, these interactions must be identified conceptually, and weak links noted in sketches and field notes.

Concluding Thoughts

Structural evaluation is not just a technical formality, it is the **moment of truth** in which the condition, geometry, and material quality are distilled into quantifiable performance. The process brings objectivity to judgment and gives clarity to retrofit decisions. It also allows structural engineers to advocate convincingly for action—whether that means reinforcing a vulnerable wall, bracing a parapet, or upgrading diaphragm connections.
Done right, this step gives engineers the confidence that their interventions are based not on assumptions or fears, but on rigorous, context-sensitive calculations grounded in the actual behavior of the structure.

2.4 System Behavior and Connectivity

Understanding how URM buildings actually resist forces—as a whole, not in parts.
Alright, so here's the thing: when you're sizing up some crusty old unreinforced masonry (URM) building, you can't just eyeball a few walls and call it a day. That's like checking your car's tires but ignoring the engine—pointless. Buildings don't stand up to gravity or earthquakes as a bunch of solo acts; they're a team, for better or worse. If you don't look at how all the messy bits actually work together—or don't—you're missing the plot. This is especially true for URM buildings, where it's not just about how tough the bricks are, but whether everything's even holding hands in the first place.

Now, compare that with newer buildings—those have steel bones and stiff floor slabs, so you pretty much know how forces are gonna flow. Old URMs? Forget it. Most of them went up in the 1800s or early 1900s, back when "engineering" was mostly guesswork and a prayer. They leaned on heavy bricks and sheer habit. And get this: the floors and roofs, usually skinny timber joists, were just plopped into the walls with little more than hope holding them in. Fast-forward a century or so—wood shrivels up, mortar starts splitting, and temperature swings make everything wiggle around. Joints open up where nobody wanted them to. Suddenly, the building's not so much a structure as a collection of detached parts ready to bail at the first sign of trouble. Yikes.

Floor and Roof Diaphragms: The Load Transfer Engine

Alright, let's get real about diaphragms in old unreinforced masonry (URM) buildings. You know those horizontal bits? Usually wood floors or roofs. Their whole job is to shove earthquake or wind forces sideways into the walls so the building doesn't crumple like a soda can. When they're actually doing what they're supposed to, diaphragms send all that shake-rattle-roll into the shear walls in both directions, helping the place stay upright.

But, yeah—historic URM construction? The diaphragms are kind of a mess. Sometimes they're just bendy planks or joists laid down with zero actual support, literally just chilling on the inner edge of the wall. No bolts, no ties, nothing. Sometimes, they're rotted out or eaten by termites (yum), or just plain falling apart because nobody's given them a second thought in fifty years.

So, when an earthquake hits and those diaphragms aren't stiff or solidly attached, guess what? They break away from the wall, and suddenly the whole thing is on its own. No teamwork. No force-sharing. Each wall is basically fending for itself, which is a recipe for collapse—like, textbook disaster. This is honestly one of the top reasons URM buildings just fall apart during quakes.

If you're poking around one of these buildings, you've gotta hunt for any sign of connections: anchor bolts, steel straps, old ledger beams embedded in the brick, or just sad-looking joists sitting on a ledge, ready to bail the second things get shaky. Best spots to check? Beam pockets, holes in the ceiling, creepy attic corners. The main goal for the engineer is to figure out if the floor or roof is actually acting as a diaphragm—or if it's basically useless and needs to be modeled as flexible (or straight-up disconnected) in analysis software like ETABS. Because, yeah, sometimes you're not working with much.

Wall-to-Wall Connectivity: Shear Continuity or Isolation?

URM walls are supposed to keep a building from toppling sideways—but that only works if they're actually tied together. Corners, T-junctions, those weird spots where interior walls meet? Yeah, the way the bricks are put together there pretty much decides if one wall can bail out the other when things get dicey.

Sometimes you get lucky and the old builders overlapped the bricks, so everything's woven together nice and strong. But, honestly, a lot of older places just slapped walls next to each other—no interlocking, just "Hey, you stand here." Over the years, as the building settles or gets rattled by a little earthquake, cracks creep in right where those walls meet. Suddenly, one wall's trying to move and the other one's like, "Nope, not my problem," which is exactly how buildings start falling apart.

If you're poking around as an engineer, you gotta check:
- Intersections—are the walls actually woven together, or is there a creepy little crack running the length of the joint?
- Parapets and cross-walls—do they lock in, or is one just doing its own thing?
- Interior partitions—are they braced into the main walls, or are they off in their own world?

If you spot gaps or separation, you might have to bust out some stitching anchors or steel ties to force those walls to work together again. Otherwise, you're just asking for trouble.

Vertical Load Path: Are Loads Going Where They Should?

Another vital aspect of system behavior is the **gravity load path**. In an ideal world, roof and floor loads travel down through joists, into load-bearing walls, then to the foundation. But in URM buildings, past modifications, settling foundations, or deteriorated headers can disrupt this path.
Common concerns include:

- Cracked or bowing walls causing joists to shift and load unintended walls,
- Removed partitions or chimney chases that previously carried part of the load,

- Floor levels out of alignment, causing redistribution of forces.

In such cases, vertical load sharing becomes uneven, and overstressed wall segments may crack or lean. The engineer must assess this redistribution and determine whether secondary members are carrying more than they were meant to. If necessary, shoring or redistribution through retrofit interventions is warranted.

Diaphragm-Wall Anchors: The Hidden Heroes

Let's get real for a sec: In every old unreinforced masonry (URM) building, the million-dollar question is—are these dang walls actually connected to the floors or roof, or are they just holding hands and hoping for the best? Forget fancy load transfer talk for a minute—this is straight-up about whether the walls are gonna stay put when the ground starts shaking. Out-of-plane wall collapse? Yeah, that's the classic URM faceplant when earthquakes hit, usually 'cause nobody bothered with solid anchorage.

So, if you poke around retrofit jobs (the good ones, anyway), you'll find all sorts of clever hardware: steel rods, chunky plates, or those sneaky epoxy bolts tying the floors back to the brick or block. Sometimes you can spot 'em—little metal plates dotting the outside of the building. Other times, especially if it's some precious historic spot, they're all hidden away like secret agent stuff. But, honestly, a ton of these old buildings? Nada. Zip. No anchors at all.

If you're poking around as an engineer (or just a paranoid building nerd), you gotta watch for a few red flags:
- Weird gaps where walls should meet floors,
- Sketchy vertical cracks creeping up corners or near where the joists sit,
- Wall tops that sway or flex when you push on 'em (or even when it's just windy, yikes).

Codes these days—ASCE 41 and the rest—don't mess around. They really, really care about these connections. You can check off all the fancy seismic boxes, but if those walls aren't tied down? Yeah, the whole thing's still a ticking time bomb.

The System Is Greater Than the Sum of Its Parts

In essence, the system behavior and connectivity check is about **structural collaboration**. URM buildings, when behaving as a system, can perform better than any isolated wall would suggest. But when connections are lost—whether due to time, damage, or original neglect—the structure becomes a set of unstable, uncommunicative components.

Professional engineers must look beyond wall strength and crack patterns to understand whether the building acts together—or alone—when forces are applied. They must identify weak links in the load path and reinforce them to restore collective action.

This systems-level insight is what elevates a good assessment into a great one. It guides meaningful retrofits, prevents collapse, and often makes the difference between preserving a heritage asset or writing it off as unsafe.

3. Chapter 3: ETABS Modeling of Orthotropic Masonry Walls

Here's the thing with old-school URM buildings—like, the ones you see lurking around from the era when everyone wore hats and nobody texted. If you're an engineer trying to retrofit these cranky old bricks, you're basically wrestling with a beast that doesn't play by today's rules. Forget about code-compliant lateral systems; these walls were stacked up long before anyone dreamt up modern structural software. Plus, the materials? Yeah, they've been aging, cracking, and generally doing their own thing for over a century.

Now, if you're messing around in ETABS, here's where it gets weird: masonry walls don't act the same in every direction. Push on them vertically, and you get one response. Nudge them sideways, and it's a whole different story—thanks, mortar joints. That's orthotropy for you: basically, the wall's got split personalities depending on which way the force is coming from. And trust me, once those walls have cracked and lived through a few dozen winters, that directional quirkiness only gets worse. So, if you wanna model these old URMs right, you've gotta dig into that orthotropic behavior and make sure your software actually gets it. Otherwise… well, good luck convincing the building to behave.

3.1 What Makes Masonry Orthotropic?

Old masonry walls tend to remain stronger in the **vertical direction**, primarily because that's the direction of brick stacking and gravity compression. These bricks, pressed together over decades, still retain some stiffness. However, the **horizontal direction**—across the weaker mortar bed joints—often exhibits significantly reduced strength and stiffness, particularly after decades of weathering, moisture infiltration, and thermal cycling.
Additionally, most structural damage from seismic action—such as diagonal shear cracks or wall separation—exploits this horizontal weakness. When modeling, engineers must reflect this reality by assigning different stiffness properties in each direction.

3.2 Step-by-Step: Modeling Orthotropic URM Walls in ETABS

1. Geometry and Wall Elements

In ETABS, masonry walls are typically modeled using **shell elements**. These two-dimensional objects are capable of carrying both in-plane and out-of-plane forces. You begin by drawing walls according to their actual location, dimensions, and features—windows, doors, spandrels, parapets, etc.
Openings are important. They break the wall into **piers and spandrels**, which behave differently under lateral loads. Accurately modeling these sub-elements helps in assessing stress concentrations and understanding the progression of damage.

2. Mesh Density

Once the walls are defined, you must **mesh** them—dividing them into smaller panels so that deformations and stresses can be captured. As a rule of thumb, use mesh elements in the range of **300 to 500 mm** for detailed analysis. Smaller mesh sizes improve accuracy but increase computational time.
Fine meshing is especially important near:

- Large openings,
- Stress concentration zones
- Cracked areas,
- Core retrofitting locations (e.g., center core bars).

3. Assigning Orthotropic Material Properties

Now comes the critical part—defining **orthotropic shell materials**. In ETABS, each shell element can be given a unique material definition with different stiffness values in the X (horizontal) and Y (vertical) directions.

For example:

- **Vertical modulus (Ev)** might be set at 1500 MPa (based on in-situ flat-jack testing or laboratory prism testing).
- **Horizontal modulus (Eh)** is usually much lower—perhaps 400 MPa—due to weaker mortar joints.
- **Shear modulus (Gxy)** could be around 150 MPa, especially in cracked masonry.

These values aren't arbitrary—they should reflect material testing when available or be derived from research literature, such as ASCE 41 commentary or FEMA guidelines. The **Ev/Eh ratio** can range from 3:1 to 5:1 in many historical buildings.

This directional stiffness simulates the way these walls actually resist seismic forces: strong vertically, weak horizontally.

4. Defining Diaphragm Behavior and Constraints

Masonry walls do not act in isolation. Their performance is tightly coupled to how the **floor and roof diaphragms** interact with them.

In ETABS, each floor level must be modeled either as:

- **Rigid diaphragm** (if there's a concrete slab),
- **Semi-rigid diaphragm** (for nailed wood sheathing),
- Or **flexible diaphragm** (common in older timber-framed floors).

Choosing the wrong diaphragm type can distort load paths. Most URM buildings have flexible diaphragms unless they've been retrofitted.

Important Note : Connections between the diaphragm and the wall must also be represented. If there are no steel ties or anchors, the wall may displace independently during an earthquake. This should be reflected in boundary conditions at floor-wall intersections.

5. Nonlinear Hinge Assignment

ETABS supports nonlinear behavior through **hinge definitions**, which simulate how a wall will crack, yield, and eventually fail.

For URM walls, you must follow these:

- Assign **shear hinges** near mid-height of piers to model diagonal cracking.
- Assign **moment hinges** at the top and bottom of piers to simulate rocking or flexural cracking.
- Use ASCE 41 backbone curves to define stiffness, strength, and ductility.

These hinges provide insight into the **performance level** of the structure—whether it meets **Life Safety**, **Collapse Prevention**, or better. They also help you simulate post-yield behavior, showing how the wall redistributes loads as it cracks.

6. Modeling Center Core Retrofit Bars

If the wall is being retrofitted using **center core grouted reinforcement**, this can be modeled in two ways:

- **Embedded vertical frame elements**, inserted inside the wall shell and connected at each floor level,
- Or by **modifying the shell material stiffness** to reflect the improved behavior.

The embedded bars add flexural capacity in the out-of-plane direction and contribute to in-plane shear strength. Make sure to include development length and grout properties when defining the behavior of these bars.

In pushover or time history analysis, these bars shift the failure mode from brittle shear to more ductile rocking or flexural yielding.

****VERY IMPORTANT SUMMARY of the ETABS MODELING**

How to Capture the Orthotropic In-Plane Behavior and Out-of-Plane Flexural Behavior of Old, Cracked Unreinforced Masonry (URM) Walls in ETABS ?

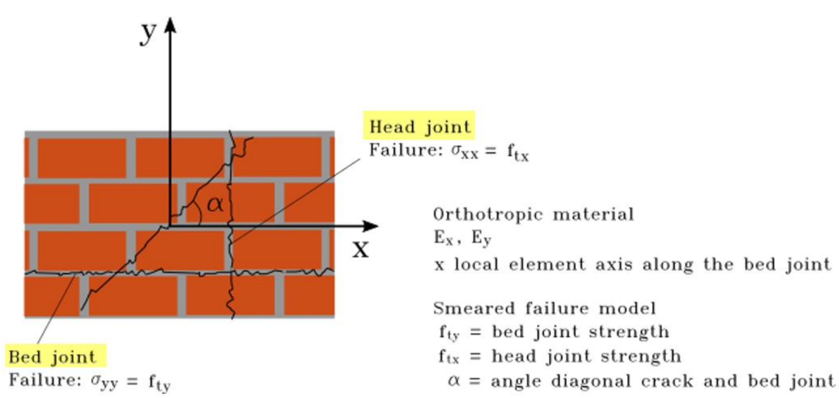
A- **ASCE 41 stiffness modifiers** for modeling unreinforced masonry (URM) walls using shell elements in ETABS

Wall Condition	Axial (F11)	Flexural (F22/F33)	Shear (F12/F13)
URM (cracked)	0.2	0.2	0.4
URM (moderately damaged)	0.1	0.1	0.2
URM (uncracked, low damage)	0.3	0.3	0.5

B- Detailed Refinement for ETABS Modeling of Old and Cracked URM Walls

Step 1: Define Orthotropic Shell Section

- in ETABS: Define > Section Properties > Shell Section
- Set **directional moduli** to reflect brick bed joint direction(see figure below):
  - **E1 (weaker axis)** – typically **10–25%** of Ebrick (~150–500 MPa)
  - **E2 (stronger axis)** – typically full masonry modulus (~1500–2000 MPa)
  - **G12** (shear) – use: G = 0.4 × min(E1, E2) / (1+ν) where ν ≈ 0.2



Step 2: Assign Local Axes for Shells

- Make sure that **bed joint direction** aligns with ETABS local axis **1 (x-dir)**
  - Use Set Shell Local Axes in Assign > Shell

Step 3: Assign Reduced Stiffness Modifiers

Use Assign > Shell Stiffness Modifiers for each wall shell panel:

Modifier Type	Value (Cracked Wall)
Membrane F11 (Axial x-dir)	0.2
Membrane F22 (Axial y-dir)	0.2
Membrane F12 (Shear)	0.4
Bending F11 / F22 (OOP)	0.2

This reflects reduced stiffness due to existing cracking.

Step 4: Out-of-Plane Flexural Behavior

- Model with **shell bending stiffness active** (plate action)
- Use **semi-rigid diaphragms for roofs (slabs)** to enable wall-diaphragm interaction
- If diaphragms are flexible (e.g., wood), tie wall tops with **horizontal line springs or gap elements**
- For walls with tie rods or overlays (FRCM, shotcrete), increase F11/F22 to **0.4–0.6**

<u>**Notes:**</u>

- Use **mesh size ≤ 0.75 m** for wall panels to capture accurate stress fields
- Ensure diaphragms are **meshed** and connected via **shared nodes**, not rigid constraints

7. Running the Analysis and Reviewing Output

After defining materials, geometry, loading, and boundary conditions, you perform:

- **Linear static or response spectrum analysis** for code compliance,
- Or **pushover analysis** for nonlinear performance evaluation.

The **pushover curve** shows how the structure deforms under increasing lateral load. It identifies which elements reach failure first, how plastic hinges develop, and whether the structure meets target performance objectives.

You should review:

- Hinge rotation demand vs. capacity,
- Wall drift ratios (especially at piers),
- Out-of-plane deflection limits,
- Diaphragm demands and load paths.

<u>If unexpected hinge failures appear (e.g., brittle shear failure in critical piers), you may need to revise your retrofit strategy or add confinement.</u>

****AFTER THE ABOVE ANALYSIS BY ETABS WHAT ARE THE IMPORTANT CHECKS?**

SIX REQUIRED CHECKS are:

1-URM Wall Behavior Checks

a. In-Plane Shear & Flexural Stresses

- Display shell results:
  Display > Shell Stresses > Membrane Forces (F11, F22, F12)
- Check:
  - **F12 (Shear)**: Compare to in-plane shear capacity of cracked URM.
  - **F11 / F22 (Axial/moment)**: Useful in walls with piers and spandrels.

For cracked URM walls, use **ASCE 41-23 Table 11-15 for allowable shear stresses or nonlinear hinge limits.

b. Crack Patterns / Stress Concentration

- Use Principal Stress contours (S11/S22)
- Look for:
  - Diagonal tension cracking (X-pattern)
  - Stress at corners, around openings

2-Out-of-Plane Wall Stability

a. Vertical Flexural Demand (F33, M11/M22)

- Display Shell > Plate Forces
- Confirm that **out-of-plane moments** are within the flexural capacity of wall sections.
- Focus on **spandrel zones** and **wall tops** where diaphragm anchorage is critical.

b. Out-of-Plane Deflection

- Display Deformed Shape under gravity + seismic.
- Check:
  - Are unbraced walls **bowing out** excessively?
  - Are diaphragm supports properly modeled?

Excessive out-of-plane deflection signals potential collapse risk or anchorage failure.

3- Diaphragm Response (Semi-Rigid)

a. In-Plane Shear Flow

- Display > Slab > Slab Forces (Vx, Vy)
- Check:
  - Shear transfer across diaphragm
  - Force path to walls
  - Weak diaphragm zones (e.g., old wood planks vs. plywood overlay)

b. Deformed Shape (Pushover or EQ case)

- Look for:
  - Torsional response (diaphragm twisting)
  - Diaphragm drift

  - Gaps or unconnected nodes

4-Performance Check per ASCE 41 (If Nonlinear Analysis)

a. Pushover Curve

- Check base shear vs. roof displacement (Capacity Curve)
- Compare to **target displacement** from ASCE 41:
  - IO / LS / CP performance levels
- Use FEMA 356 or ASCE 41 hinge limits (plastic rotation, shear strain)

b. Hinge Status (If Hinges Used)

- Display Hinge > Force-Deformation Status
- Check:
  - % of walls in **Life Safety (LS)** or **Collapse Prevention (CP)** states
  - Failure concentration at piers, spandrels, or wall ends

5-Global Building-Level Checks

Item	**Check**
Story Drift (Seismic)	≤ allowable per ASCE 7 or ASCE 41 (e.g., 0.01–0.02 for URM)
Torsional Irregularity	Review displacement and shear at corners
Base Shear	Compare to code-based demand or ASCE 41 demand
Mode Shapes	1st three modes should reflect expected translational and torsional behavior
Stability	Check P-Delta effects if high drift, especially in tall walls

6-Anchorage & Wall Connectivity

- URM walls must be:
  - Tied to diaphragms (roof/floor)
  - Laterally braced or anchored
  - Connected across wythes (if multi-wythe)

Check:

- Support conditions at top/bottom of walls
- Beam-wall and diaphragm-wall nodes

Common Mistakes to Avoid

Finite element modeling of URM walls are very important and complicated issues, than concrete. So, professional designers must be careful and attentive to the following:

1. **Assuming masonry is isotropic**: Never model old URM walls with the same stiffness in all directions. It leads to misleading results.
2. **Using rigid diaphragms by default**: Old timber floors are rarely rigid unless retrofitted.
3. **Ignoring weak connections**: If the floor isn't anchored to the wall, you must model it accordingly.

4. **Overlooking orthogonal seismic load effects**: Out-of-plane collapse is common during real earthquakes—account for it.
5. **Over-refining the mesh without justification**: It slows down analysis but doesn't always improve accuracy.

Conclusion: Engineering Judgment Above All

Look, ETABS is a pretty powerful tool, but let's not kid ourselves—it's not gonna do your job for you. The magic? That's all in how you take what you see out in the field, all those old-school tricks you picked up from folks who've been around, and the latest test data, and then actually turn it into something that makes sense inside the software. Slapping on orthotropic properties, fiddling with nonlinear hinges, tweaking diaphragms—yeah, those aren't just button clicks. That's where your engineering gut comes in.

Especially when you're dealing with retrofitting unreinforced masonry stuff, you can't just check a box and call it a day. Modeling turns into this whole brain workout. If you treat ETABS like it's just another step in the process, you're missing the point. Do it right, and suddenly you can see where things might break, find ways to actually keep people safe, and end up with a design you're not embarrassed to defend. And hey, maybe it won't fall down in the next big one. That's the real win.

4. Chapter 4: Overview of Retrofitting Methods for URM Walls

4.1 The Nature of URM Wall Failures – Why Retrofit?

Alright, let’s break this down without all the textbook stiffness.

First off—if you wanna slap some retrofitting on a URM (Unreinforced Masonry) wall, you gotta know how these suckers actually fail when an earthquake comes knocking. Otherwise, you’re just throwing money at bricks.

So, here’s the deal. URM walls tend to go down in flames (not literally, but you get me) in two main ways when the ground starts shaking:

1. **In-Plane Shear Failure**
You ever notice those skinny bits of wall between windows? Yeah, those are trouble spots. When things get shaky, they don’t just politely crack—they split up diagonally, like someone took a giant axe to them at a 45° angle. No rebar means those bricks and mortar joints can’t hold it together. Suddenly, you’re not looking at a wall anymore, just a sketchy pile of bricks that’s lost the plot. No warning, just boom—gone.

2. **Out-of-Plane Bending Failure**
Here’s another classic: the wall just starts bulging out or tipping over, especially if it’s tall and thin. If the wall isn’t locked in tight to the floor or roof, it starts doing its own solo dance routine during an earthquake. Parapets (those cute little wall extensions at the top) and upper sections are usually the first to bail—no surprise there, since they’re barely hanging on to begin with.

So, what do engineers do? They come up with retrofit tricks to stop all this chaos. Basically, they try to make the walls bend more before breaking (fancy term: ductility), hug the bricks together tighter (confinement, baby), bolt the walls to the rest of the building (anchorage), and just generally beef up their side-to-side strength. All this, while still keeping the building from looking like Frankenstein’s monster.

Long story short: if you wanna fix a URM wall, you gotta know its favorite ways to fail first. Otherwise, you’re just patching holes in a sinking ship.

<u>Center Core Retrofitting – (</u><u>*effective way)*</u>

Honestly, this trick is kinda underrated—super effective, super sneaky, and you can use it a bunch of ways. So, here’s how it goes: you drill these pretty small holes (like, somewhere around 75 to 100 mm wide) straight down the middle of the wall. Usually right in the center, so you don’t mess up the look or the finishes. Then you shove in some rebar (#5 or #6, take your pick), and it runs all the way from the foundation up to the diaphragm. After that, you pump in this soupy, high-strength grout to glue everything together.

The cool part? The rebar basically turns the wall into a tag-team. Steel takes care of tension; masonry does its thing with compression and shear. Out-of-plane? That vertical steel helps the wall bend without snapping. In-plane? You're getting way more ductility, and the cracked piers aren't flopping around as much.

If you're modeling this in something like ETABS, you toss in some embedded frame elements inside your shell elements for the cores. The steel beefs up the wall's flexural and shear stiffness, messes with how hinges behave, and just generally stops the wall from giving up and cracking apart too early.

Couple things to watch out for:

- Drilling's gotta be careful, or you'll blow out the wall (especially if it's got voids or sketchy spots inside).
- That rebar needs to go deep enough at the top and bottom—don't skimp on the embedment, and make sure you're tying into the diaphragms right, maybe with hooks or plates.
- Grout needs to be on point. You want it strong, sticky, and filling everything up. Usually you grout from the bottom up and use vent tubes to make sure you're not leaving air pockets.

Advantages:

- You literally can't see it from outside.
- Doesn't really mess with the wall's thickness or how it lines up.
- Works for historic buildings—preservation folks usually don't freak out.
- And yeah, your wall's way stronger and can flex a lot more before it gives up.

4.2 Fiber-Reinforced Polymer (FRP) Systems – Understanding Behavior

FRP systems—yeah, we're talking about those crazy-strong fiber sheets (carbon, E-glass, take your pick) soaked in epoxy and slapped onto walls. The whole idea? Patch up those spots where your masonry is weakest, like along horizontal mortar joints or those sketchy diagonal cracks that love to spread.

Stick FRP on vertically, and boom: it fights off out-of-plane bending, kinda playing the role of steel rebar but without all the drama. Throw it on horizontally or diagonally, and it's basically like slapping a Band-Aid right across the cracks, stopping them from getting any worse.

<u>Couple things you can't skip:</u>
- The wall's gotta be clean, solid, and dry. If your mortar's falling apart, fix that first or you're just wasting fancy fiber.
- Fire? Yeah, FRP hates it. If things heat up, the stuff loses strength fast, so you'll probably need some fire-rated coating or maybe just bury it in plaster to keep it safe.
- If you're working on an old building—think heritage vibes—you gotta get sneaky and hide the FRP behind plaster or something pretty.
- Edge details matter big time. You can't just slap the stuff on and hope for the best. Anchor it into the returns or floor/roof diaphragms, or you're not really getting the strength boost you paid for.

Engineers, when they model this stuff, basically just bump up the wall's shear and flexural strength in their calculations. You'll also see better performance if the wall starts to yield—less "oh no, it's falling apart" and more "okay, it's hanging in there."

Real talk: FRP's like the duct tape of structural upgrades, but with way more science behind it.

Shotcrete Jacketing – A Complete Transformation

Shotcrete jacketing—it's basically slapping on a tough, new skin for your poor, fragile old brick wall. Picture this: you spray on a fat layer of supercharged concrete, packed with welded mesh or steel bars that get drilled right into the original bricks. It's not a gentle upgrade, more like a full-blown makeover with power tools. After it sets, the wall's not just old bricks anymore; now it's flexing like a reinforced concrete beast, with the old masonry just chilling in the background, along for the ride.

Best Applications:

- Severely deteriorated walls
- Industrial or utilitarian structures where appearance is not critical
- Buildings needing significant capacity upgrades to meet high performance objectives

Look, slapping shotcrete on a wall totally messes with its mass and how stiff it is—can't just ignore that if you're dealing with earthquakes. And let's be real, once you've done it, good luck trying to reverse it or keep the building's historic vibes. Not gonna happen.
You can spray that stuff on one side, or both if you're feeling wild. But here's the catch: engineers really have to double-check if the foundation can handle the extra weight. Otherwise, you might end up with some awkward settling or, worse, the whole thing tipping over. Nobody wants that mess.

Diaphragm Anchorage – The Unsung Hero of Retrofitting

No matter how strong the wall itself is, if it's not adequately connected to the floor or roof, it can still collapse outward during an earthquake. Many failures begin at the interface between the wall and diaphragm. In older URM buildings, floors were simply bearing on the wall or loosely embedded, offering little resistance to out-of-plane motion.

Modern retrofitting connects walls to diaphragms using epoxy-set threaded rods, plates, or anchor bolts. Sometimes steel drag struts or collector elements are added within the diaphragm to distribute loads across bays.

Diaphragm anchorage upgrades are essential not only for wall safety but also for enabling proper seismic load paths in the entire building.
In modeling, this is reflected by upgrading diaphragm connectivity, modifying diaphragm stiffness (rigid, semi-rigid, flexible), and capturing improved load-sharing among walls.

Combining Techniques – A Strategic Approach

Let's be real—nobody's out here fixing old buildings with just one magic trick. Engineers basically throw the whole toolbox at it and hope for the best :

• Got a cracked pier? They'll patch it up with some stitching and grout, then slap on a few FRP diagonals for good measure.
• Those skinny, wobbly walls? Yeah, they get beefed up from the inside with core bars, plus some sneaky anchors at the top to keep everything in check.
• Parapets? You know, those little walls up top that love to fall off during quakes—they'll get some hidden steel frames bolted right into the main structure.
• And if the floors are basically trampolines? Out come the plywood sheets or maybe a quick layer of concrete to stiffen things up.

This hybrid approach allows for targeted strengthening, optimized cost, and minimal disturbance to building users.

Final Reflections: Engineering beyond Codes

Retrofitting URM walls is not just about satisfying code checklists. It's about restoring confidence in buildings that have housed generations, survived decades of weathering, and witnessed community history.

Engineers must use more than calculations. We must interpret patterns of damage, envision how buildings move in space, and engage with architects, owners, and contractors to implement solutions that are safe, sensitive, and lasting.

Every bolt, grout core, or FRP strip represents a line of defense—not just against earthquakes, but against time itself.

Table 1 & Fig. 1 summarize URM Wall Retrofit Techniques and introduce a useful comparison

Table 1- URM Wall Retrofit Techniques – Summary Table (2025)

Technique	**Cost**	**Seismic**	**Reversible**	**Visual Impact**	**Heritage Use**
Center Core (Grouted Rebar)	Moderate	High	Moderate	Low	High
FRP (Fiber Wrapping)	Low-Mod	Medium	Low	Low-Medium	Medium-High
Shotcrete Jacketing	High	Very High	Very Low	Very High	Low
Crack Stitching (SS Rods)	Low	Low-Medium	High	Very Low	Very High
Grout Injection	Low-Mod	Low-Medium	High	Very Low	Very High
Diaphragm Anchoring	Moderate	High	Moderate	Low-Medium	High
Steel Bracing (Hidden)	High	Very High	Very Low	High	Low
Parapet Bracing	Moderate	High	Moderate	Low-Medium	High
Concrete Topping on Diaphragm	High	High	Low	Medium	Medium-Low

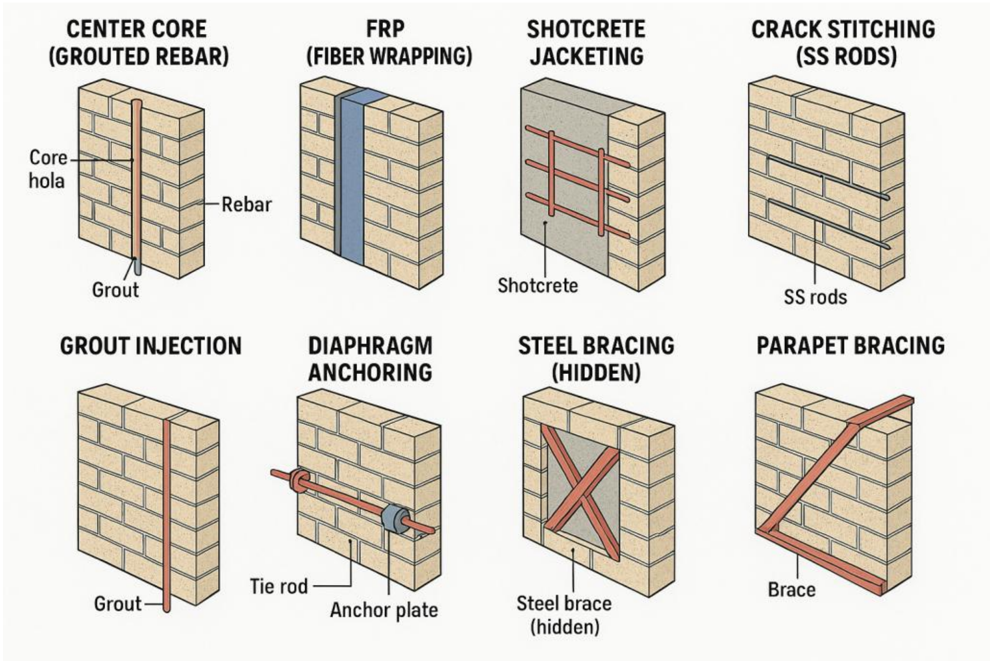


Fig. 1 - URM Wall Retrofit Techniques

5. Chapter 5: Center Core Retrofitting – Design and Analysis Example

Let's be real—when it comes to beefing up those old unreinforced masonry (URM) buildings, center core retrofitting is basically the MVP. Like, it actually does the job without trashing the building's vibe. You know how URM walls are kinda wimpy when it comes to tension and ductility? Plus, they freak out with both in-plane and out-of-plane forces. Center core retrofitting swoops in and sorts all that out, but here's the kicker: from the outside, you'd never know. No ugly add-ons, no messing with the building's look. That's why engineers in the U.S.—especially the ones dealing with old historic stuff—are all about this method. It's like a secret structural upgrade.

5.1 Understanding the Concept

Alright, here's the deal: you basically drill straight down through the middle of the URM wall—yeah, right through it—then drop in some beefy rebar. After that, you fill up those holes with some hardcore grout or epoxy stuff that doesn't shrink (because, you know, cracks are bad news). The whole point? Those hidden bars give the wall a secret backbone so it can actually handle shaking and swaying when an earthquake shows up uninvited.

And here's the beauty of it: unlike that thick shotcrete jacket nonsense, this "center core" thing doesn't mess with the wall's surface at all. The old paint, fancy trim, whatever weird historic vibe the building's got—it all stays the same. No chunky layers bulking up the inside or the outside. So, for places where looks matter—think old libraries, schools, fire stations, those grand civic buildings—this trick is a lifesaver. You keep the charm AND stop the place from crumbling.

5.2 Real-World Design Example: 1920s Two-Story Brick School in Northern California

This project involved retrofitting a two-story school building constructed in the early 20th century using solid clay brick URM walls(Fig. 2). The building had suffered seismic damage in the past and showed visible signs of diagonal cracking and mortar degradation. Wall thickness varied between 350–400 mm, with piers spaced approximately 4 m apart.

Fig. 2- 1920s Two-Story Brick School in Northern California

Step 1: Structural Assessment Findings

- Diagonal shear cracks were observed in piers between windows on the first floor.
- The in-plane shear strength was significantly below demand for a design-level earthquake per ASCE 41-23.
- Out-of-plane wall bulging was noted near parapets and mid-height zones.
- Floors were flexible timber diaphragms, poorly anchored to walls, this is a common phenomenon in URM buildings as mentioned previously.

Based on visual inspection, material testing, and ETABS modeling with orthotropic shell behavior, it was clear that a minimally invasive, yet structurally robust retrofit was required.

Step 2: Design and Detailing of Center Core Reinforcement

- **Drilling pattern**: Vertical holes, 100 mm in diameter, were drilled along the mid-thickness of critical piers, spaced at approximately 1.2 meters.

NOTES for Vertical Spacing: *The spacing of center core bars depends on wall thickness, height, and demand, usually spaced every 1.2 to 2.4 meters (4 to 8 feet).*

- **Bar selection**: #5 Grade 60 bars (16 mm diameter, f_y = 414 MPa) were inserted.

NOTES for Bar Size: *Typically, #5 to #8 (No. 16 to No. 25) ASTM A615 Grade 60 bars are used depending on the required capacity.*

- **Bonding**: Holes were flushed, cleaned, and pressure-grouted with non-shrink epoxy grout (compressive strength > 40 MPa, bond strength ≥ 1.5 MPa).

NOTES for Grout and Bonding

× ***Grout Type***: *A low-shrink, non-sand or fine aggregate cementitious grout with high flowability is used, complying with ASTM C476 and having compressive strength typically ≥ 20 MPa (3000 psi).*

× ***Grout Placement***: *Pumped from the bottom of the core upward using tremie tubes to ensure complete void filling and bond.*

× ***Bonding with Masonry***: *To maximize interaction, the drilled core should roughen the internal masonry and penetrate across units and mortar joints.*

- **Anchorage**: Bars extended into the foundation with 300 mm hook embedment, and up into diaphragm zones with mechanical anchorage to roof/floor systems.

NOTES for Development Length*: The bar must be fully developed in grout and anchored into the foundation or a transfer beam below, and preferably extended into a roof or floor diaphragm at the top.*

- **Corrosion Protection**: Epoxy-coated or stainless steel bars are recommended for durability, especially in coastal or high-humidity environments.

Step 3: Analytical Verification

To ensure the retrofit met performance objectives, the wall piers were evaluated using both hand calculations and finite element modeling in ETABS.

A. In-Plane Shear Strength Improvement
Each bar contributes additional shear capacity:

$$V_{add} = A_s \cdot f_y \cdot \sin(\theta)$$

Assuming vertical bars only (θ = 90°):

$$A_s = \pi \cdot (16\,\mathrm{mm})^2/4 \approx 201\,\mathrm{mm}^2$$
$$V_{add} \approx 201 \cdot 414 = 83.2\,\mathrm{kN\ per\ bar}$$

With three bars per pier:

$$V_{total} \approx 3 \cdot 83.2 = 249.6\,\mathrm{kN}$$

This was more than enough to meet the Tier 3 shear demand under ASCE 41-23 Life Safety performance.

B. Out-of-Plane Flexural Capacity
Retrofit bars also act as internal tension reinforcement in bending, which is critical for walls subjected to out-of-plane seismic forces. Moment capacity was checked assuming the bar acts like tension steel in a vertical cantilever:

$$M_n = A_s \cdot f_y \cdot (d - a/2)$$

where:

- d is wall thickness (e.g., 380 mm)
- $a = A_s \cdot f_y/(0.85 f'_m \cdot b)$

Even with conservative assumptions, the wall's flexural capacity increased over 2.5 times post-retrofit, verified with ETABS pushover curves.

Step 4: ETABS Modeling Integration
In ETABS, each wall pier was modeled using **orthotropic shell elements** (Ev/Eh = 4.0 ratio based on flat-jack tests). Vertical reinforcement was represented using **embedded nonlinear frame elements**, connected across shell nodes. Plastic hinges were assigned based on ASCE 41-23 for:

- **Shear (V–γ)**
- **Flexure (M–θ)**

Pushover analysis showed:

- Reduced interstory drift
- Improved hinge distribution (flexural hinges forming before shear failure)
- Capacity curve shifted to higher base shear and displacement

This indicated a ductile failure mechanism had been achieved, with a performance level between **Life Safety (LS)** and **Immediate Occupancy (IO)** depending on diaphragm anchorage conditions.

Step 5: Construction Notes

- Dust and vibration during drilling were controlled with vacuum shrouds.
- Work was performed from the interior side to preserve historic exterior brick façades.
- Bars were anchored into new steel collector beams at diaphragm levels to ensure effective force transfer.

Construction was completed with minimal disruption to school operations, and the building passed a follow-up seismic safety evaluation.

Benefits and Limitations
Benefits:
We can summarize the benefits of this way as high structural efficiency **,** low visual impact, compatibility with historic buildings and improved ductility and energy dissipation
Limitations:
Its limitations require skilled drilling to avoid cracking, anchoring at floor/roof may need modification, and less effective for walls with severe delamination or voids

Conclusion

Center core retrofitting is a proven, minimally invasive technique that provides substantial improvements in both in-plane and out-of-plane capacity for URM walls. When properly designed, detailed, and integrated into structural analysis models like ETABS, it can elevate an otherwise vulnerable building to a safe and code-compliant performance level—without compromising its architectural integrity. For structural engineers tasked with the retrofit of heritage or civic buildings, this method remains a cornerstone of effective seismic rehabilitation.

6. Chapter 6: Software Recommendations for URM Analysis

Successfully assessing and retrofitting URM buildings requires the use of multiple software tools—each chosen for its strengths in modeling, analysis, documentation, or detailing. No single software can do it all. Instead, engineers rely on a combination of finite element platforms, macro-modeling programs, drafting tools, and custom analysis scripts to produce accurate and code-compliant results.

ETABS (by CSI) remains the primary engine for full-building analysis of URM structures, particularly for seismic evaluation. It offers the ability to model orthotropic behavior through shell elements with directional stiffness, assign nonlinear hinge definitions, perform pushover analyses, and simulate performance under real-world loading scenarios. ETABS also integrates well with ASCE 41-based performance assessments, making it especially useful for retrofit design.

TREMURI or **3Muri** (widely used in Europe but increasingly referenced in U.S. research) apply the equivalent frame method to URM walls, converting wall piers and spandrels into nonlinear elements. These tools are ideal for global analysis of complex masonry buildings with many openings and varied geometry. Though not as flexible as ETABS, they are efficient for seismic ranking studies or comparative analysis of retrofit strategies.

DIANA FEA is a powerful finite element package that supports nonlinear, detailed micro-modeling of masonry. For engineers needing insight into local wall behavior—such as crack initiation, propagation, and interface failure—DIANA offers more granularity than ETABS. It is especially useful when simulating laboratory validation models or justifying design assumptions with advanced mechanics.

AutoCAD and **Revit** are indispensable for producing drawings, retrofit detailing, and coordination with architects. Most construction documents—including section views of grouted cores, tie anchorage, or shotcrete overlays—are still developed in CAD environments.

In parallel, **MATLAB** or **Excel-based tools** play a support role. They are essential for sensitivity studies, analytical cross-checking, generating capacity curves, or automating checks for Tier 1 and Tier 2 assessments. Custom spreadsheets are especially helpful when validating ETABS outputs or when testing the impact of parameter variations.

Finally, for documentation and communication, tools like **Bluebeam** (for markup) and **PDF drafting utilities** assist in preparing retrofit proposals, submittals, and annotated field reports.
The key is not which software is best, but how each tool is used in combination. A skilled engineer must move fluidly between modeling platforms and manual checks, using software to amplify—not replace—engineering judgment. URM assessment and retrofitting demand this multi-tool mindset to ensure safe, economical, and context-sensitive design solutions.

7. Chapter 7: Structural Retrofitting Applications for URM Buildings – U.S. Case Histories

Case Study 1: Garfield Elementary School – Salt Lake City, Utah, USA

Garfield Elementary isn't just some crusty old brick box—it's got that classic 1920s vibe, sure, but under all that charm, the place is kind of a disaster waiting to happen. You walk by those two stories of red brick and think "Oh, cute!" but, yeah, the building's basically held together by hopes and dreams. Turns out, those brick walls? They're not reinforced at all—just stacked up, no real connection to the roof above. The inside and outside layers of brick (wythes, if you wanna get technical) aren't even tied together, which means in an earthquake, they could just split apart and do their own thing. And the roof? Wood-framed, barely attached, and about as sturdy as a soggy cardboard box when it comes to handling sideways shaking. Generations of kids made it through, but honestly, it's a miracle the building's still standing.

So, instead of just bulldozing the place or totally wrecking its vibe, the engineers came up with a fix that—honestly—feels kind of genius. First off, they slid in these near-surface mounted (NSM) steel reinforcements (check out Fig. 3 if you're feeling nerdy). Basically, they cut a bunch of grooves—both sideways and up-and-down—right into the inside brick walls. Then, they crammed high-strength steel bars in there with a ton of epoxy, like they were super-gluing the whole thing together. These bars basically worked as a steel skeleton, lashing the inside and outside layers together and beefing up the wall so it wouldn't flop over in a strong wind. Once all those metal bars were snug in their little brick cocoons, they sprayed on a chunky 2 to 3-inch layer of structural shotcrete—think of it as high-powered concrete frosting—which wrapped around the steel grid and made everything way tougher and more flexible. Pretty slick, honestly.

So, after that, they tackled the diaphragm issues. Basically, the old wood joists up on the roof? They slapped on a layer of structural plywood, turning it into a solid, continuous diaphragm (way sturdier than before). Then they added steel collectors around the outside, bolted right into these new concrete bond beams. Those beams weren't just floating there either—they were locked straight into the beefed-up walls, making sure earthquake forces had a legit path from the roof all the way down to the foundation.

And get this—the school didn't even have to shut down while all this was happening. Huge deal for the district, honestly. The whole upgrade hit the ASCE 41-13 "Life Safety" mark, which is the gold standard for keeping people safe in earthquakes, especially in public schools. Plus, they managed to save all the cool old details inside and out, so Garfield Elementary ended up as kind of a poster child for how to retrofit unreinforced masonry schools without turning them into ugly bunkers. Even the Utah Seismic Safety Commission gave them a shoutout, showing you really can pull off safety and historic vibes at the same time.

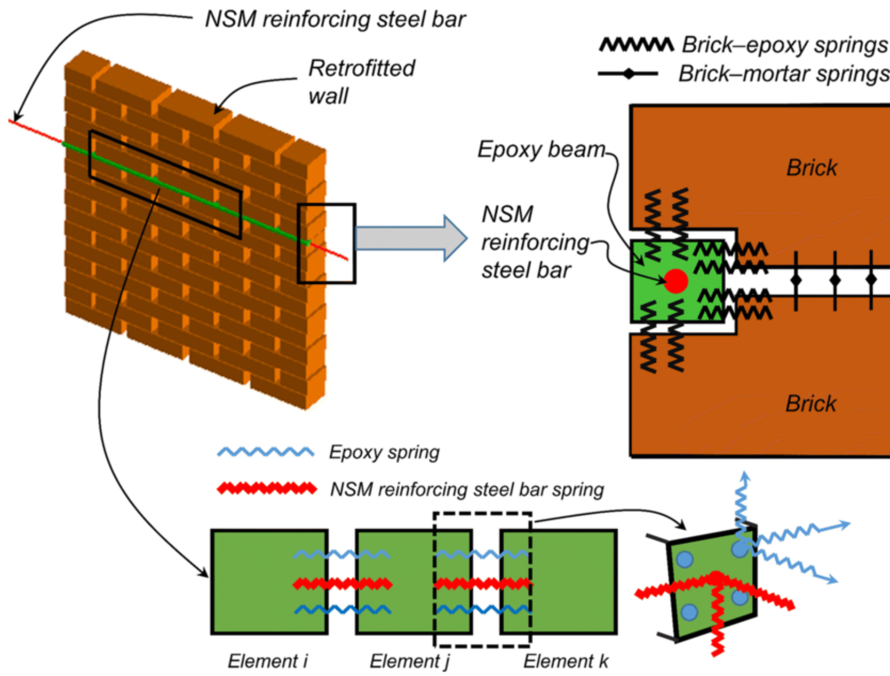


Fig. 3- installation of near-surface mounted (NSM) steel reinforcement

<u>Case Study 2</u>: Napa County Historic Courthouse – Napa, California, USA

Alright, let's talk about the Napa County Courthouse. This place has been hanging around since 1878—yeah, it's old-school. We're talking thick, unreinforced brick walls, fancy brick details, big arched windows, timber holding things up, and those super tall parapets on top. It's pretty much the poster child for California's pre-1900 public buildings.

Then, in 2014, the South Napa Earthquake came in swinging. The courthouse took a real beating—chunks of parapet fell off, cracks zig-zagged through the walls, and some of the floors literally pulled away from the walls. Basically, it was a mess, and all that damage just screamed, "Hey, maybe someone should've given this building better support and connected things a little tighter." (See Fig. 4 if you wanna get nerdy about it.)

Alright, so here's the deal: this courthouse is one of those old beauties—historic status and all—so the retrofit team couldn't just go in there swinging sledgehammers or slapping on whatever new tech they felt like. They had to keep things looking OG while making sure the place wouldn't crumble in the next shake.

Instead of blasting the walls with shotcrete or wrapping everything in plastic-like FRP (which, honestly, would've been a crime against those gorgeous old finishes), the engineers picked this FRCM stuff—basically, a thin, tough mortar with a special mesh inside. It beefs up the walls without making them chunky or hiding the original brick and stone vibe. You barely even see it, unless you know what you're looking for.

And they weren't about to risk a disaster, so first they built a sample wall right there on-site. Tested the hell out of it—will it stick, will it breathe, does it pass the "does this look weird" test? Once all boxes were checked, the real work started: FRCM went up on the inside of the most stressed-out wall sections, especially near floors and doors. Those spots take the most abuse in a quake. This move amped up the building's flexibility, so instead of snapping, it'll kind of wiggle and absorb energy. Smart.

Where chunks of wall had already bailed out (thanks, gravity), they filled in with lightweight CMUs that actually matched the old stuff—color, size, the whole shebang. Not just slapped in either; they left space for things to move and tied it in with steel dowels so the new bits don't act like dead weight.

Oh, and they got sneaky with these fiber anchors, tucking them into corners where floors meet walls. That way, everything's locked together without ugly hardware showing.

Put all this together, and the courthouse got a new lease on life—passed the big ASCE 41-17 "Life Safety" hurdle and even got a thumbs up from California's emergency folks and the local history buffs. Now it's kind of a poster child for how you can earthquake-proof an old landmark without turning it into a concrete bunker. Not bad, right?

Fig. 4- Structural cracking of Napa County Historic Courthouse after 2014 South Napa Earthquake

Case Study 3: Memorial Firehouse No. 1 – San Francisco, California, USA

Built way back in 1915, Firehouse No. 1 isn't just some ordinary old building—it's basically a downtown San Francisco time capsule that still has to spring into action when things go sideways. The place was put together with unreinforced clay bricks and old-school wood framing, so, yeah, not exactly the poster child for earthquake safety. You've got these giant bay doors for the fire trucks that practically scream "please collapse me," plus walls that love to crack after a good shake, and a roof that's barely hanging on in terms of structural teamwork.

To reinforce the building while preserving its historic character, engineers implemented a multi-pronged approach:

Core-Grouted Steel Rods
In strategic locations—especially between apparatus bays—vertical steel rods were drilled through the full thickness of the wall and epoxied into place. The rods tied the inner and outer brick wythes together, significantly improving out-of-plane stability and preventing wall separation during seismic tremors(Fig, 5).

Embedded Steel Moment Frames
At large bay openings, hidden steel moment frames were installed directly within the masonry. These internal frames carried bending stresses during lateral shaking without impacting the historical exterior façade.

Roof Diaphragm Strengthening
The existing timber roof diaphragm was upgraded with a layer of structural plywood. Then, steel tension straps were anchored between the diaphragm and the wall's reinforced bond beam, creating a cohesive load path that ties the roof into sidewall stabilization.

Designed to meet **FEMA 356 Life-Safety performance objectives**, these interventions secured the building's functionality as an emergency facility while honoring its aesthetic legacy. That success earned industry praise for balancing engineering rigor with heritage protection.

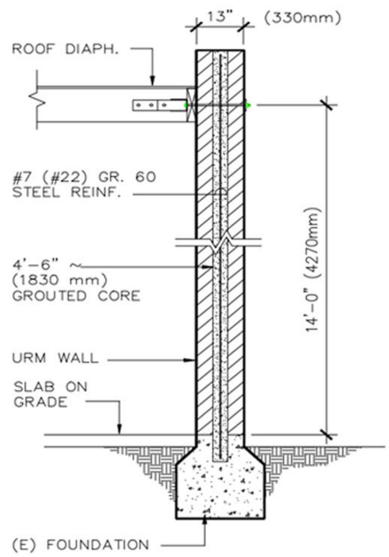


Fig. 5- Typical wall cross-section : core-grouted steel rod spanning the wall thickness (green), embedded steel moment frame around the opening (gray), plywood diaphragm overlay, and steel strap anchorage tying diaphragm to wall top

What These Case Studies Teach Us

Honestly, if there's one thing these projects hammer home, it's that seismic retrofits for old unreinforced masonry buildings are never cookie-cutter jobs. Every building's got its own quirks, and you can't just slap on the same fix everywhere and call it a day. The engineers who actually get it right? They're the ones who:

- Get their hands dirty, really digging into what's there and what isn't.
- Pick retrofit methods that actually make sense for how the building's put together and what people use it for.
- Talk—a lot. Not just with each other, but with owners, city folks, the preservation diehards, and the folks swinging the hammers.
- Stress-test their ideas with everything from computer simulations (think ETABS) to old-school lab tests, and aren't afraid to have someone else double-check their math.

But here's the kicker: It's not all about ticking boxes on some building code checklist. This stuff matters because it saves lives, keeps neighborhoods looking like themselves, and makes sure our cities aren't just piles of rubble when the ground goes sideways. That's the real point—keeping people safe, sure, but also holding onto the places that matter to us.

8. Chapter 8: Conclusion – Preserving Structures, Protecting Lives

Retrofitting unreinforced masonry (URM) buildings? Oh man, that's a wild ride in the engineering world. These old brick beauties—think a hundred years old, give or take—are everywhere you look in cities and small towns across the U.S. We're talking about the backbone of Main Street: old courthouses, schools, firehouses, city halls, the works. They look gorgeous, sure, but let's not kid ourselves—they're one good shake away from a pile of bricks.

The crazy part? Tons of these buildings are still in use, pretty much unchanged. Nobody bothered to give them a real structural facelift, even though they were never built for the kind of earthquakes we know can hit places like California, Washington, Utah... heck, even parts of the Midwest and East Coast aren't off the hook. It's not just a bunch of engineers wringing their hands—this is a legit safety issue. But at the same time, these places are dripping with history and character. So it's a tricky balance: how do you keep people safe without bulldozing a century of civic pride? There's no easy answer, but man, it's not something you can ignore.

8.1 The Engineer's Role: Between Code and Craft

Man, structural engineers—they're basically juggling a million things at once. There's code stuff, performance demands, and, for the old-school buildings, all the headaches of historic preservation. With new buildings, it's all smooth sailing: you get your blueprints, your fancy materials, all the details spelled out. But start poking around in an ancient unreinforced masonry (URM) building and it's a whole different ballgame. No paperwork. Random construction quirks everywhere. Secret voids. Mortar that's probably older than your grandma. Plus, layers of weird fixes and "updates" slapped on over the decades by who-knows-who.

One thing this course keeps hammering home—just following the building code isn't enough when you're retrofitting URM buildings. Nope, not even close. You gotta do way more:

- Actually pay attention to how the building's used, its funky shape, and what makes it worth keeping around in the first place.
- Don't trust the walls—test everything, inspect on-site, really dig in to figure out what's going on.
- Make sure your design doesn't just barely hold up, but actually bends instead of breaking (ductility, baby), can take a hit from any direction, and can be fixed after the fact.
- And forget about cookie-cutter models—break out the good software (think ETABS or DIANA), and model the real deal, with all the weird material behavior and wild earthquake responses you'll get with old brick and mortar.

It's messy work, but honestly? That's what makes it interesting.

8.2 Challenges Ahead—and Why You Matter

The demand for URM assessment and retrofit is only increasing. Municipalities, school districts, private owners, and federal agencies are now aware of the liability posed by these aging structures. Funding mechanisms, such as FEMA's BRIC program or local resiliency initiatives, are now available to support retrofitting projects. However, the availability of qualified structural engineers who understand both performance-based design and heritage preservation is limited. **You, as a trained professional, now stand at the forefront of this responsibility.**

This course has provided you with:

- The **technical tools** (nonlinear analysis, orthotropic modeling, capacity checks).
- The **design strategies** (center core reinforcement, FRP, diaphragm retrofitting).
- The **decision-making framework** (assess > model > design > justify > communicate).
- And most importantly, the **confidence to approach URM retrofitting with clarity and integrity.**

8.3 A Final Word: Engineering as Preservation

Retrofit design is not simply a structural upgrade. It is an act of preservation, a statement of value for the community, and a gesture of engineering respect for the legacy of the past. We are not merely strengthening walls—we are **extending the lives of buildings** that have served generations and should serve many more.

Your work on URM structures will protect students, firefighters, civic workers, and families. And when the next earthquake strikes—because it will—these upgraded buildings will stand because you made the decision to assess carefully, model faithfully, and retrofit responsibly.

Let this course not be an endpoint, but the beginning of your active contribution to seismic safety and architectural preservation in the United States.

9. References

1. **ASCE 41-23** – Seismic Evaluation and Retrofit of Existing Buildings. American Society of Civil Engineers, Reston, VA, 2023.
2. **FEMA P-154** – Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook, 3rd Edition. FEMA, 2015.
3. **FEMA 356** – Prestandard and Commentary for the Seismic Rehabilitation of Buildings. FEMA, 2000.
4. **ACI 530 / TMS 402/602** – Building Code Requirements and Specification for Masonry Structures. The Masonry Society and ACI, latest edition.
5. **International Building Code (IBC)** – International Code Council, latest edition.
6. **CSI ETABS** – ETABS User and Technical Manuals. Computers and Structures Inc., Berkeley, CA.
7. Lourenço, P.B. – Computational Strategies for Masonry Structures. Delft University, 1996.

10. APPENDIX A:

FIELD INSPECTION CHECKLIST FOR URM BUILDINGS

(To be used by structural engineers during preliminary surveys)

A. General Building Information

- ☐ Building Name/ID: ___________________________
- ☐ Address/Location: ___________________________
- ☐ Year of Construction (estimated): ___________
- ☐ Number of Stories: _______
- ☐ Building Use (e.g., school, fire station, storage): _____________
- ☐ Seismic Zone (per ASCE 7 map): _____________
- ☐ Known Modifications / Repairs: _____________

B. Masonry Wall Condition

For each wall or section, check and document the following:

1. Visual Defects

- ☐ Vertical cracks (Record location, length, width)
- ☐ Diagonal (shear) cracks
- ☐ Horizontal cracks (especially near floors, roof, or parapet)
- ☐ Stair-step cracks through masonry units or joints
- ☐ Open joints or missing mortar
- ☐ Spalling, delamination, or erosion of brick faces

2. Out-of-Plane Deformations

- ☐ Wall bulging outward/inward
- ☐ Misalignment between upper and lower stories
- ☐ Disconnection between wythes (if multi-wythe)

3. Mortar Quality

- ☐ Mortar easily scraped or powdered
- ☐ Evidence of repointing (Good or Poor quality?)
- ☐ Presence of lime-based mortar or early cement

4. Openings & Stress Concentrations

- ☐ Cracking around windows/doors
- ☐ Inadequate or missing lintels
- ☐ Large or asymmetrical openings

C. Floor and Roof Diaphragm Interface

- ☐ Visible anchors or ties into walls
- ☐ Separation between floor/roof and wall

- ☐ Type of diaphragm (wood, steel, concrete)
- ☐ Diaphragm stiffness (Rigid / Semi-rigid / Flexible)
- ☐ Any sign of movement or sagging

D. Parapets, Chimneys, and Other Appendages

- ☐ Free-standing parapets or poorly anchored ones
- ☐ Cracked or leaning chimneys
- ☐ Loose or deteriorated elements at roofline

E. Environmental Deterioration

- ☐ Signs of moisture ingress (staining, efflorescence)
- ☐ Moss, mold, or biological growth on walls
- ☐ Freeze-thaw cracking (especially on north side)
- ☐ Corrosion stains from metal elements (e.g., embedded anchors)

F. Safety Notes

- ☐ Any immediate hazard or structural instability observed?
- ☐ Restrict access required? Yes / No
- ☐ Photos taken of each wall? Yes / No
- ☐ Drone inspection needed? Yes / No