Seismic Rehabilitation of Existing Unreinforced Masonry Buildings

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The Masonry Society
AIA Provider: 505119857

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  - Fred Turner (former CSSC and ASCE 41-14/17 masonry lead)
  - Kent Yu (SEFT)
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Historic Background

- Unreinforced masonry buildings (URM)
  - Large inventory of buildings in areas of high seismicity
- California has led the way
  - URMs Banned after the 1933 Long Beach earthquake
  - Mandatory retrofit programs
    - Local ordinances, such as Division 88 in LA
    - 16,000 buildings retrofitted between 1970s and 2000s
    - Documents evolved to IEBC, ASCE 31/41

Largely based on the ABK (Agbabian, Barnes, and Kariotis) reports from the 1970s-1980s

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Performance of Retrofitted URMs

- In Northridge (1994) and South Napa (2014) earthquakes
  - Retrofitted URM buildings did better than unretrofitted, but still:

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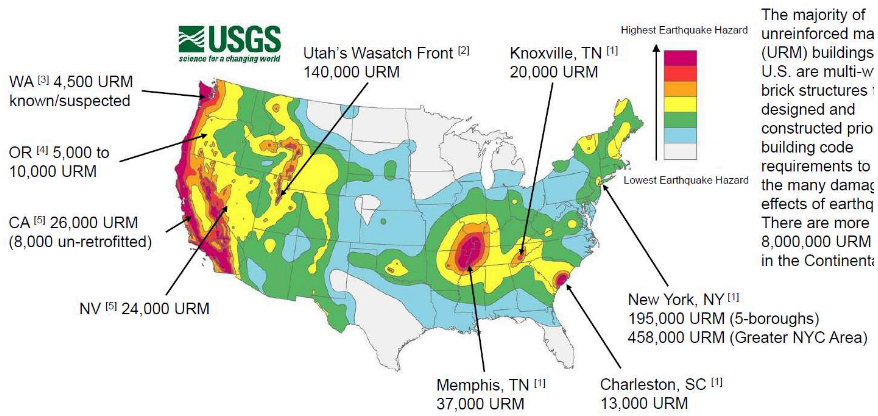
An Issue Beyond California

- Large Inventory
  - Over 8M URM buildings in the US
  - High vulnerability
  - Many in areas of high seismicity
  - No major update of retrofit guidelines in ~40 years
- **Focusing on retrofitted buildings in California**
- Modular methodology can be used for other cases once modules are adjusted



Issues with Current Guidelines

- Are often prescriptive
- Lack rigorous validation from
  - 3-d dynamic tests
  - detailed FE analyses
- Do not consider
  - Recovery time
  - Repair cost

Project Scope

A **3-year experimental** and **numerical/analytical** study to improve the resilience of existing URM buildings by developing reliable design guidelines and decision-making tools for the **effective retrofit** of these structures considering the **life-cycle cost**.

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Project Tasks

- Task 0
  - Information regarding the design prototype structures
- Task 1
  - Experimental program focusing on 3-d behavior of retrofitted structures
- Task 2
  - Detailed and simplified simulation tools
- Task 3
  - Fragility curves
- Task 4
  - Life-cycle/resilience-based decision guidelines
- Task 5
  - Technology Transfer

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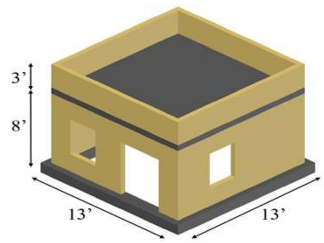
Timeline of Experiments

- 03/2020
  - Design the prototype structure(s) and selection of materials
- 07/2020: Material tests
- ~~04/2020~~ 11/2021
  - Component tests
- ~~11/2020~~ 03/2022
  - 1st shake table test: representative of existing retrofit schemes
- ~~10/2021~~ 10/2022
  - 2nd shake table test: “resilient” retrofit schemes



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Background Needed for a Realistic Study

- Design of prototype structures
  - Dimensions, design details
- Representative material properties
  - As built/current properties?
  - Masonry units
  - Mortar

- Pick realistic retrofit schemes
  - FRP overlays/strips
  - Strong backs
  - Moment frames
  - Concrete jacketing
  - Coring
  - Neat surface mounted bars

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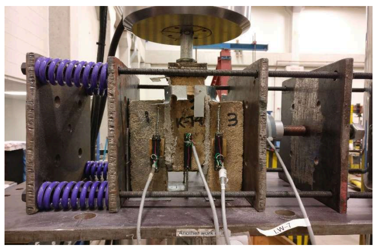
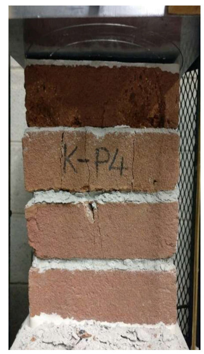
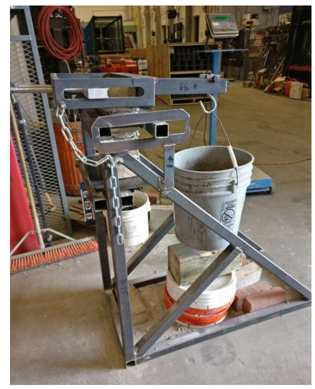
Material Tests

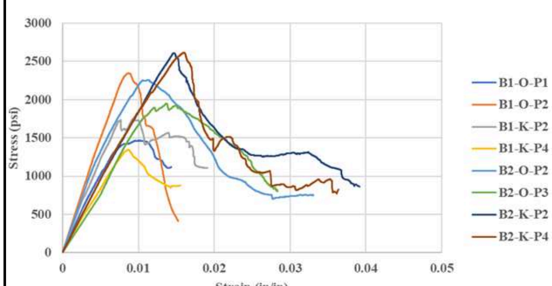
- Material tests on masonry assemblies
  - Shear tests on triplets
  - Bond wrench tests
  - Prism compression tests

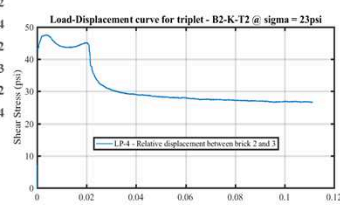


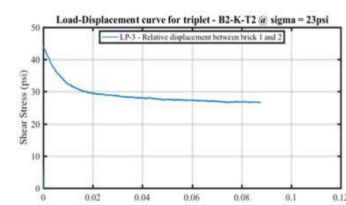


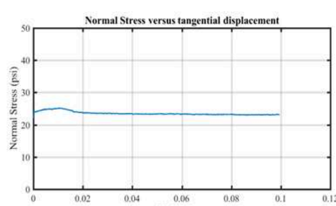


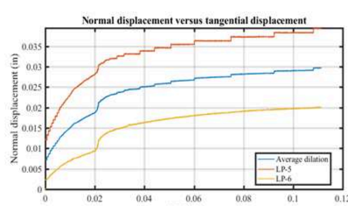
Prism and Triplet Test Results









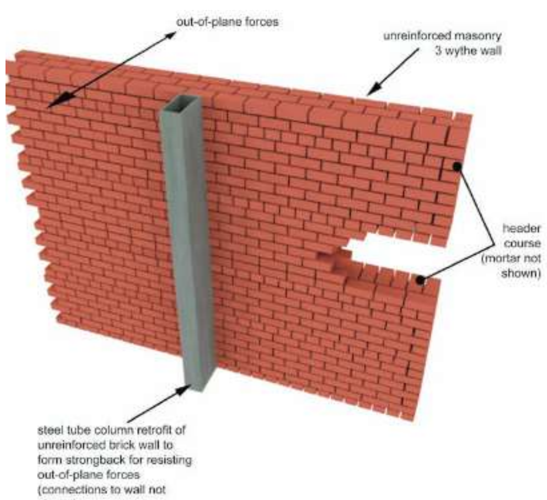


Background Needed for a Realistic Study

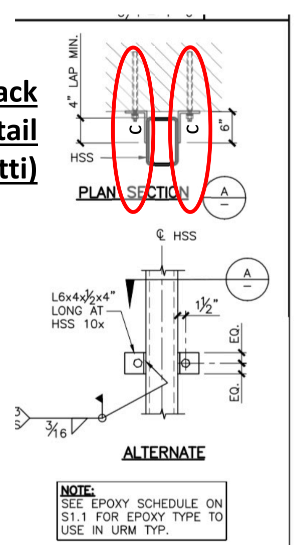
- Design of prototype structures
  - Dimensions, design details
- Representative material properties
  - As built/current properties?
  - Masonry units
  - Mortar
    - Type K

- Pick realistic retrofit schemes
  - FRP overlays/strips
  - Strong backs
  - Moment frames
  - Concrete jacketing
  - Coring
  - Neat surface mounted bars

Common Retrofit: Strong Backs



Strong-Back connection detail (Thorton-Tomasetti)



Information Available to Designers

Product			Page No.	Tested Base Materials and Code Listings: Concrete – Cracked	Concrete – Uncracked	Concrete on Metal Deck	CMU – Grout-Filled	CMU – Hollow	Unreinforced Clay Brick Masonry	Other	Other Listings
Mechanical Anchors	Titen HD® (THD)		52	ESR-2713, RR25741, FL-15730.6			ESR-1056, RR25560, FL-15730.6	IBC	—	—	FM, DOT
	NEW Stainless-Steel Titen HD® (THD-SS)		56	ER-493			ESR-1056, RR25560, FL-15730.6	IBC	—	—	FM, DOT
	NEW Titen HD® Countersunk Screw Anchor		58	ESR-2713, RR25741, FL-15730.6			ESR-1056, RR25560, FL-15730.6	IBC	—	—	FM, DOT
	Titen HD® Rod Coupler (THD-RC)		60	Non-IBC	—	—	—	—	—	—	—
	Strong-Bolt® 2 (STB2)		62	ESR-3037, RR25891, FL-15731.2		ESR-3037 RR25891 FL-15731.2	ER-240, RR25936 FL-16230.4	—	—	—	UL, FM, DOT
	Wedge-All® (WA)		66	—	Non-IBC	Non-IBC	ESR-1396, FL-15730.7	—	—	—	UL, FM, DOT

Anchoring, Fastening Systems and Restoration Solutions for Concrete and Masonry

Product Selection Guide

SIMPSON Strong-Tie

Limitations in Provided Information

Table 14 - Hilti HIT-HY 270 allowable adhesive bond loads for threaded rods in multi-wythe solid brick wall[1,2,3,4,5,6,8]

Nominal anchor diameter in.	Effective embedment[7] in. (mm)	Tension lb	Tension (kN)	Shear lb	Shear (kN)	Minimum spacing s_{min} in. (mm)	Edge distance: Critical c_{cr} in. (mm)	Edge distance: Minimum c_{min} in. (mm)	Load reduction factor@ c_{min}
3/8	6 (152)	895	(4.0)	680	(3.0)	16 (406)	16 (406)	8 (203)	0.50
	10 (254)	1,325	(5.9)	795	(3.5)				
1/2	6 (152)	895	(4.0)	1,075	(4.8)				
	10 (254)	1,455	(6.5)	1,115	(5.0)				
5/8	6 (152)	1,025	(4.6)	1,405	(6.3)				
	10 (254)	1,955	(8.7)	1,445	(6.4)				
3/4	8 (203)	1,575	(7.0)	1,985	(8.8)				
	13 (330)	2,135	(9.5)	1,985	(8.8)				

1 All values are based on mortar shear strength of 45 psi or greater. Allowable loads are calculated using a safety factor of 5.
2 Anchors must be installed in the face of the multi-wythe URM wall. The wall must have a minimum thickness of 13 inches made up of 3 wythes of brick.
3 Tabulated values are for maximum one anchor installed in the center of the brick of the multi-wythe URM wall.
4 Edge distance, c_{min}, and spacing, s_{min}, are the minimum distances for which values are available and installation is recommended. Edge distance is measured from the center of the anchor to each edge. Spacing is measured from the center of one anchor to the center of an adjacent anchor.
5 Allowable loads must be the lesser of the adjusted bond tabulated values and the steel values given in table 3.
6 Allowable loads shall be adjusted for increased base material temperature in accordance with Figure13.
7 Tabulated embedment depth is limited by the length of the plastic HIT-SC screens.
8 For combined loading: $(T_{applied} / T_{allowable}) + (V_{applied} / V_{allowable}) \leq 1$

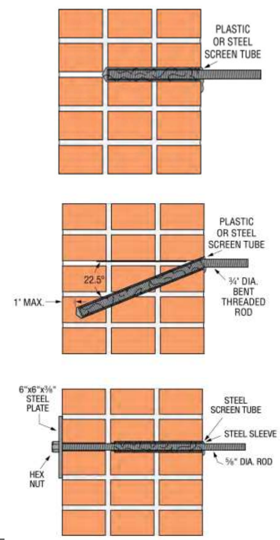
Lack of Design Guidance for Anchors

- Type of anchor
- Spacing
- Strength
- Location:
  - on mortar or brick?

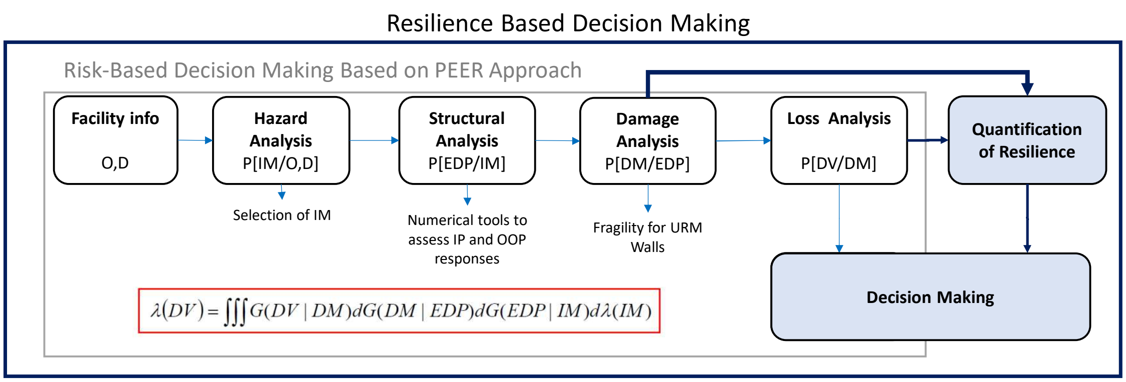
Straight

@ 22.5 deg

Through anchors w/ end plate



Framework for Decision Making



$$\lambda(DV) = \iiint G(DV \mid DM)dG(DM \mid EDP)dG(EDP \mid IM)d\lambda(IM)$$

- DV: Decision Variable - $ losses, downtime, casualties
- DM: Damage Measure - Physical condition and performance functions
- EDP: Engineering Demand Parameter - : Story drift, floor velocity, floor acceleration
- IM: Intensity Measure - PGA, PGV, Sa(T_1), vector of Sa's
- O: Location, D: Design, RI: Resilience Index

Intensity Measure

Hazard Analysis → Structural Analysis → Damage Analysis → Loss Analysis → Resilience

Selection of IM — Commonly used → PGA, SA(T)

→ Possible IMs for URM → PGA, PGV, SA(T), average SA

Single or Multiple IM ?

Are different IMs correlated?

Damage Behavior of structures

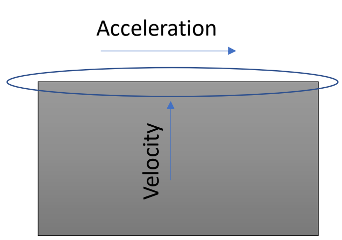
Acceleration driven
In plane damage

Velocity Driven
Out of plane damage

IM in Perpendicular Directions

Hazard Analysis → Structural Analysis → Damage Analysis → Loss Analysis → Resilience

- Good correlation for PGA-PGV in the same direction
- Are ground acceleration and velocity in perpendicular directions correlated?



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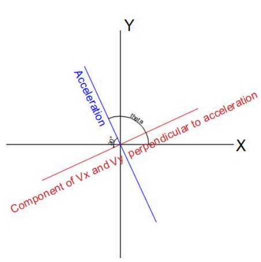
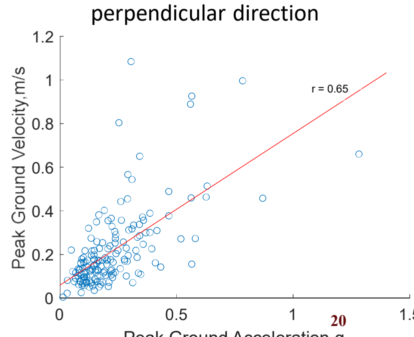


PGA-GV in perpendicular direction



Structural Response of Retrofitted URMs

Hazard Analysis
Structural Analysis
Damage Analysis
Loss Analysis
Resilience

Response of URM

In-Plane and Out-of-plane response

Component Level

System Level

Experiments

Detailed FE Modelling

Simplified Modelling

Structural Response of Retrofitted URMs

Hazard Analysis
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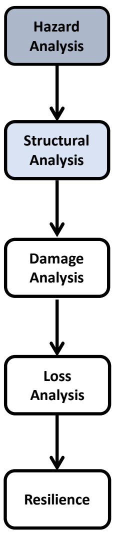
Anchor Pullout Tests

Dynamic Tests of URM Walls with Strongbacks

Shake table tests of two buildings

Design of Test Structures



- URM buildings in California retrofitted around 1980s
  - H = 15’-0”
  - 3-wythe (13”)
- Wall width limited to ½ of the wall height
- Future shake table tests with similar prototype
  - Weight limitation on the table
  - Hence scaled to 2:3

Height=10’-0”

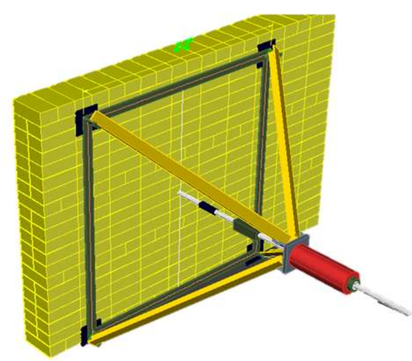
Thickness=8” (2-wythe)

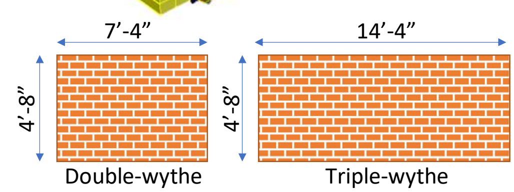
Width=5’-0”

Static pullout tests for anchors

- Test cases and wall dimensions

Sl.No	Wall Thickness	Anchor embedment	Anchor Dia	Test Type	Location	Anchor Type
1	8"	6"	0.5	confined	Mortar	Straight
2	8"	6"	0.5	confined	Brick	Straight
3	8"	6"	0.5	un-confined	Mortar	Straight
4	8"	6"	0.5	un-confined	Mortar	22.5 deg
5	8"	6"	0.5	un-confined	Mortar	Through bolt
6	8"	6"	0.5	un-confined	Brick	Straight
7	8"	6"	0.75	confined	Mortar	Straight
8	8"	6"	0.75	confined	Brick	Straight
9	8"	6"	0.75	un-confined	Mortar	Straight
10	8"	6"	0.75	un-confined	Mortar	22.5 deg
11	8"	6"	0.75	un-confined	Mortar	Through bolt
12	8"	6"	0.75	un-confined	Brick	Straight
13	13"	10"	0.75	confined	Mortar	Straight
14	13"	10"	0.75	confined	Brick	Straight
15	13"	10"	0.75	un-confined	Mortar	Straight
16	13"	10"	0.75	un-confined	Mortar	22.5 deg
17	13"	10"	0.75	un-confined	Mortar	Through bolt
18	13"	10"	0.75	un-confined	Brick	Straight





As We Speak

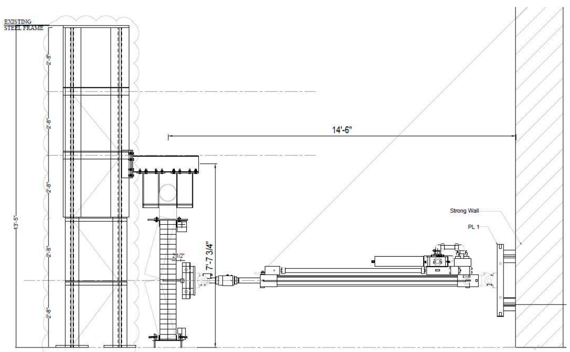
Double-wythe

Triple-wythe

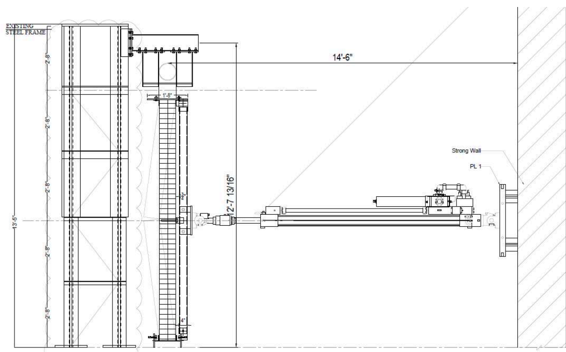
Dynamic Test Setup Elevation

Hazard Analysis → Structural Analysis → Damage Analysis → Loss Analysis → Resilience

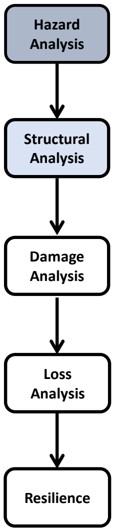
Phase - 1



Phase - 2



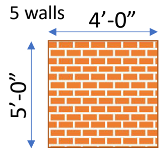
Dynamic Tests

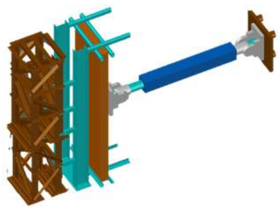


- Test matrix for Phases 1 and 2

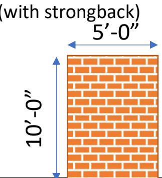
Phase	Test#	H	T	W	H/T	Anchor Diameter	Anchor Embedment	Anchor Type	Anchor Angle	Number of Anchors	Testing type	Comment
		ft	*in*	*in*		*in*	*in*					
1	1A	5	8	48	7.50	0.5	6	Epoxy	0	1	Static	Control Specimen
	1B	5	8	48	7.50	0.5	6	Epoxy	0	1	Dynamic	Control Specimen
	1C	5	13	48	4.62	0.5	10	Epoxy	0	1	Dynamic	
	1D	5	8	48	7.50	0.5	6	Epoxy	22.5	1	Dynamic	
	1E	5	8	48	7.50	0.5	6	Through bolt	0	1	Dynamic	
2	2A	10	8	60	15	0.5	6	Epoxy	0	2	Dynamic	1-Anchor at the center (Pin-Pin)
	2B										Dynamic	1-Anchor at the center (Pin-Pin)
	2C										Dynamic	Anchor at third points (Pin-Pin)
	2D										Dynamic	Anchor at quater points (Pin-Pin)

- Phase 1
  - 5'-0" tall wall (no strongback)
  - 5 walls

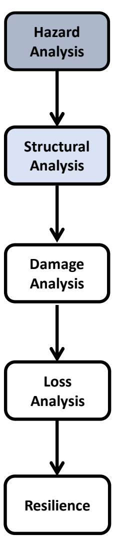




- Phase 2
  - 10'-0" tall wall (with strongback)
  - 5 walls

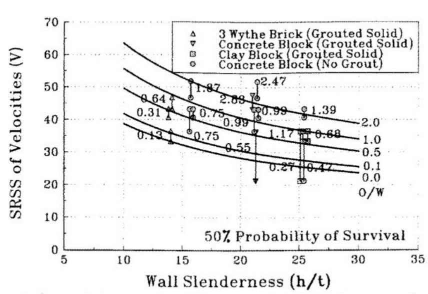


Shake-Table Tests



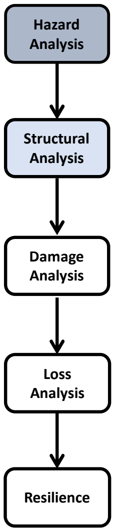
- Shake-table specimen being designed for table limits and ABK limits
  - Specimen designed so that ABK predicts failure without retrofitting

UB SEESL shaking table

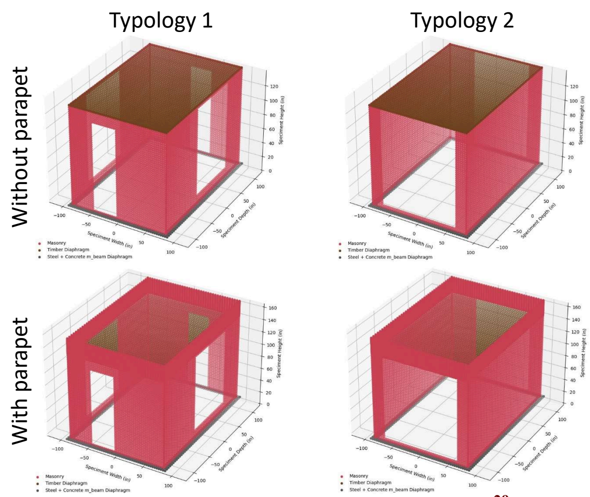


ABK test results for out-of-plane wall stability

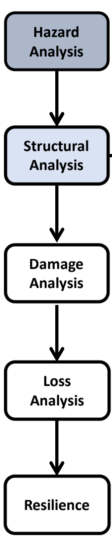
Shake-Table Tests

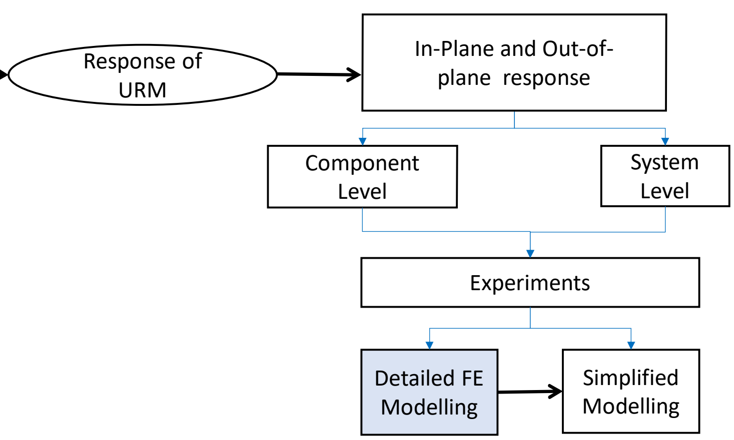


- Proposed test specimen includes two basic typologies with and without parapets
- Plan dimensions: 20’x14’
- Basic height: 11’-3”
  - Parapet height: 2’

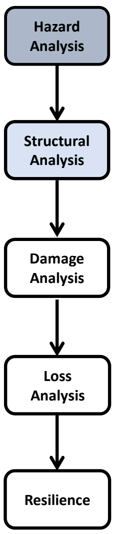


Structural Response of Retrofitted URMs



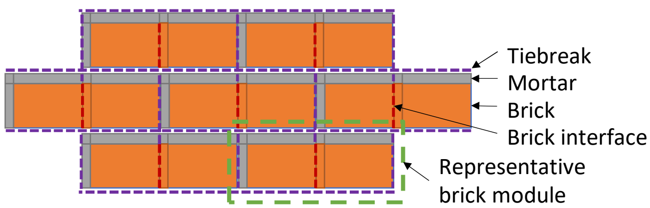


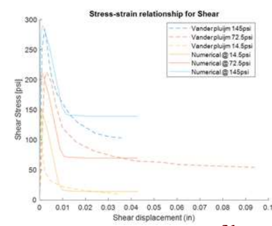
Detailed FE Model-Solid Elements



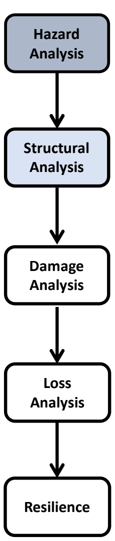
- Discretization of micro-modeling approach and its calibration

Elements/contacts	Compression	Tension	Shear
Brick	*Damage*	Linear	Linear
Mortar	Linear	Linear	*Damage*
Tie-break	None	*Damage*	None

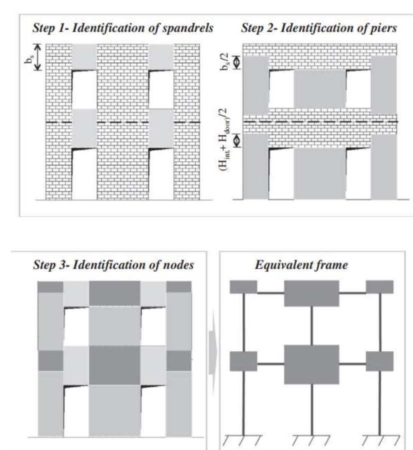




Simplified Model Using Macro-elements

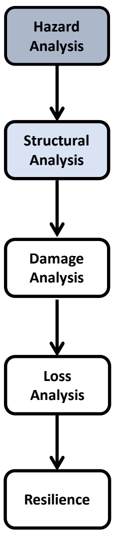


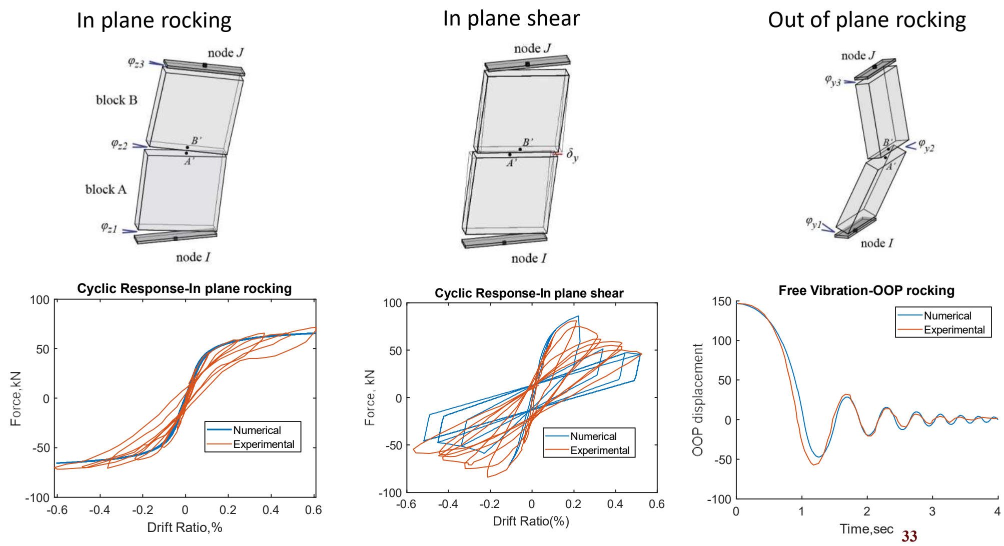
- Equivalent Frame Modelling of the Global Response
- 3-D macroelement (Vanin et. al. 2020)
- Overcomes shortcomings of the existing simplified models
  - Capture both IP and OOP response
  - Connections between wall to wall and wall to floor
- Flexible/Rigid diaphragms



Equivalent Frame Modelling of Masonry (Lagomarsino, 2013)

Macroelement Model: Modes of Failure





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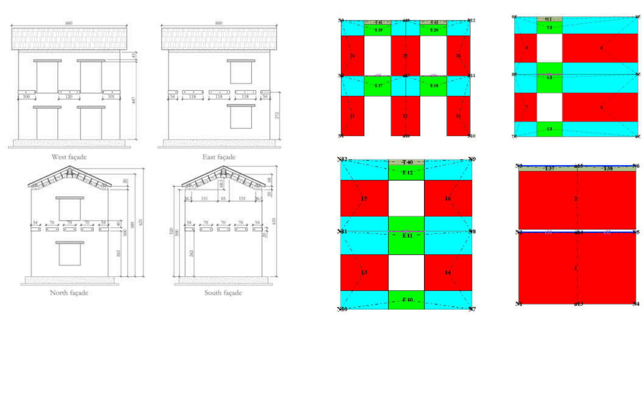
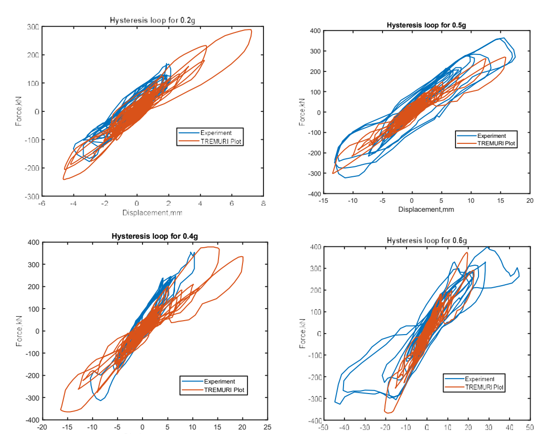
Simplified Modeling with Tremuri

Shake table test of full scale stone masonry by Magenes et al. (2010)





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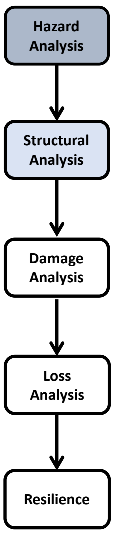
Review of Existing Test Data



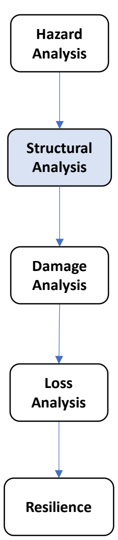
- A series of shake table tests on URM structures conducted in EUCENTRE

- ABK assumption on no ground motion amplification in-plane of wall investigated
  - Valid for low levels of shaking
  - Significant amplification after wall cracking

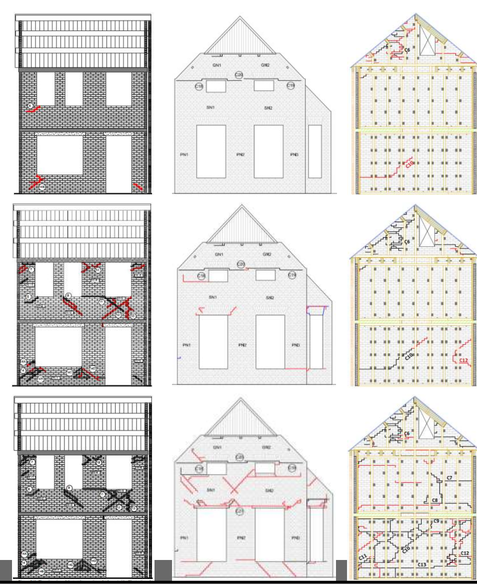
- EUC-BUILD2 to be used for FE model assessment

TEST	Shaking	Pub. Year	Description
EUC-BUILD1	Uni-directional	2015	2-Story 5.5x5.8m Cavity Wall Structure
EUC-BUILD2	Uni-directional	2016	2-Story 5.3x5.8m 2-Wythe Wall Structure
EUC-BUILD6	Uni-directional	2019	2-Story 5.2x5.9m Cavity Wall Structure (Large Openings)
EUC-BUILD7	Uni-directional	2019	Retrofitted EUC-BUILD6 (New Build)
EUC-BUILD8	Uni, Bi, and Tri-directional	2020	1-Story 4.0x4.2m 2-Wythe Structure. Corner geometries too small to manifest bi-directional effects
LNEC-BUILD1	Uni-directional	2017	1-Story 5.1x5.8m Cavity Wall Structure tested to collapse
LNEC-BUILD3	Uni-directional	2018	1-Story 5.4x5.7m 2-Wythe Wall Structure tested to collapse

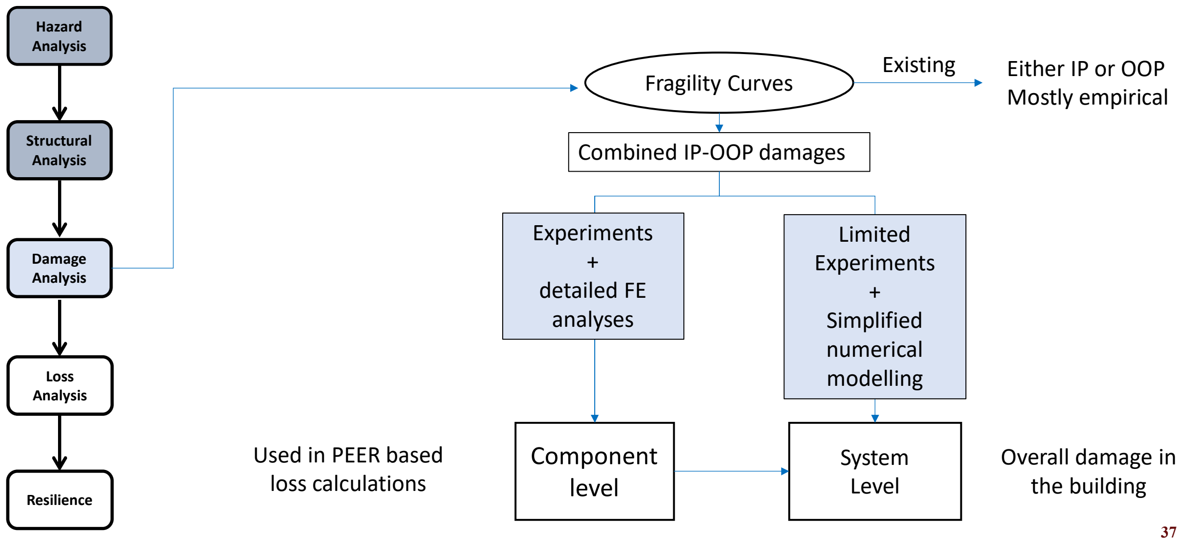
Review of Existing Test Data



- Observed damage states
  - Minor cracking
    - Residual cracks < 1mm
    - Some reduction to modal frequency (approximately 30% reduction)
  - Moderate cracking
    - Some residual cracks > 1mm
    - Large reduction to modal frequency (approximately 50% reduction)
  - Significant cracking
    - Numerous cracks > 10mm
    - Significant reduction to modal frequency (approximately 70% reduction)



Damage Analysis



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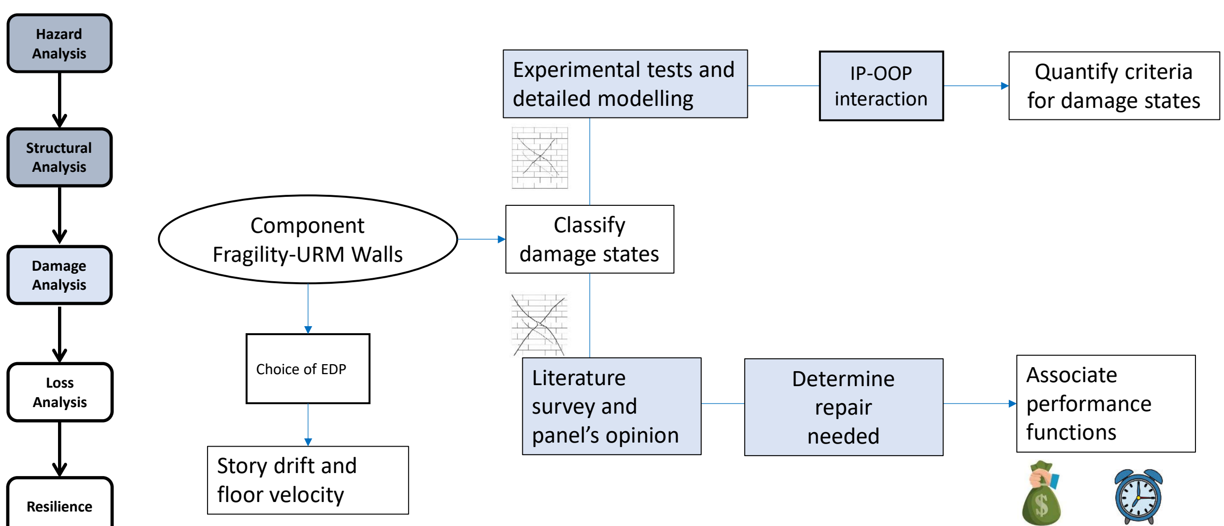
Fragility for URM Walls



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Quantification of the IP-OOP Interaction

Hazard Analysis → Structural Analysis → Damage Analysis → Loss Analysis → Resilience

$$\frac{OOP\ Capacity\ with\ IP\ force}{OOP\ capacity\ without\ IP\ force}^{1.5} + \frac{IP\ Capacity\ with\ OOP\ force}{IP\ capacity\ without\ OOP\ force}^{1.5} \le 1.0$$

Numerical Simulations

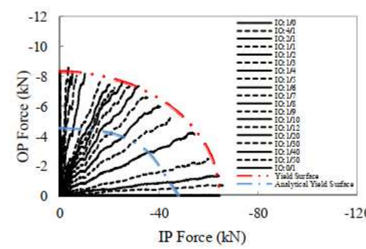
Existing

IP-OOP interaction

Interaction curve as function of EDP – For PBEE approach

Experimental Tests

Numerical simulations



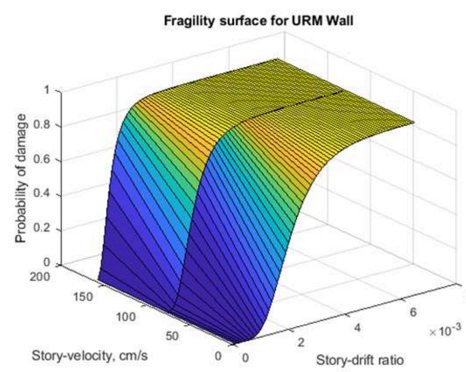
Wall pier under combined IP and OOP loading, Dolatshahi 2014

Fragility Surface for URM Walls

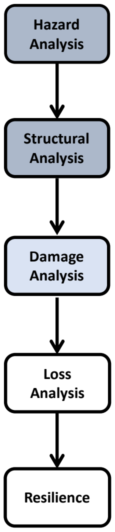
Hazard Analysis → Structural Analysis → Damage Analysis → Loss Analysis → Resilience

- Fragility surface for URM
  - If two EDP's are used the curve takes form of surface

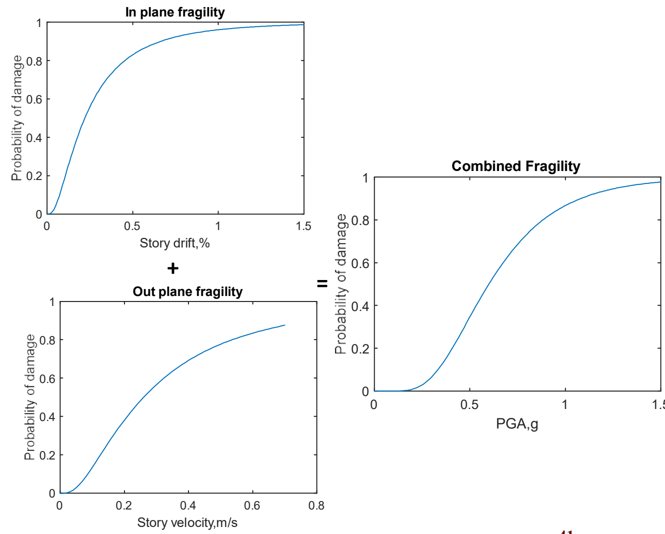
Fragility Surface for URM



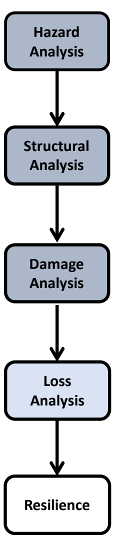
Combining Fragility Curves



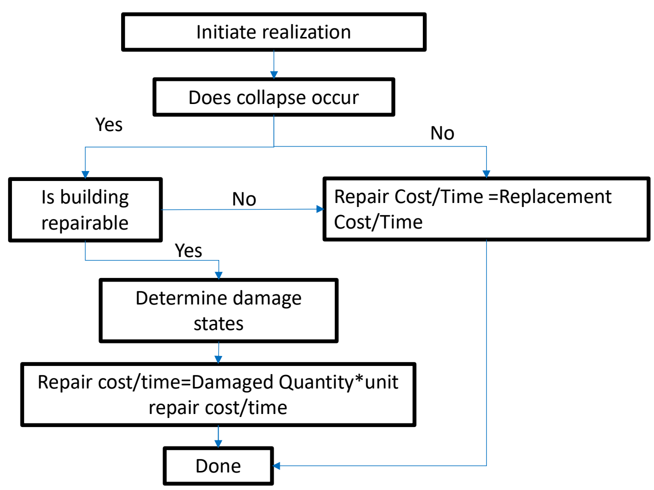
- Combining IP and OOP fragility curve
  - Methodology proposed by Nielson (2007) for combining component level fragility to system level fragility for bridges
  - Used here to combine different modes of damage for single component
  - Modified to include interaction of capacity states



Loss Analysis

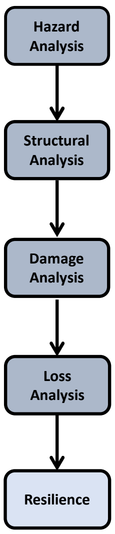


- Loss outcomes:
  - Collapse
  - Unrepairable damages
  - Repairable damages
- Intensity-based losses
- Time-based losses

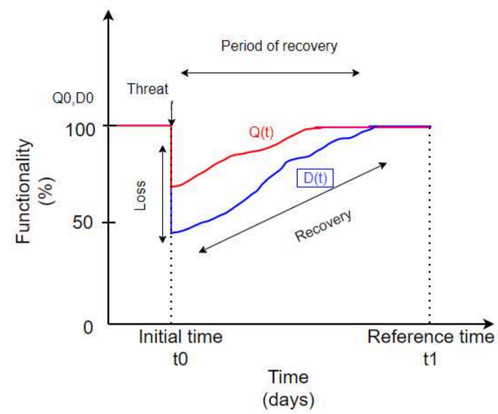


Flowchart for calculation of performance quantities (FEMA-P 58)

Quantification of resilience



- Resilience index (RI) quantified based on different functionalities
  - Downtime
  - Functionality defined by stakeholders
  - Repair Costs



Next Steps

- Conduct
  - anchor pull-out tests
  - Wall out-of-plane tests
- Finalize the design of the shake-table specimen
- Improve the numerical models
- Collect data on the repair costs/time

This concludes The American Institute of Architects Continuing Education Systems Course

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