Wildfire risk mitigation in the WUI: From ignition-resistant to fire-resistant houses

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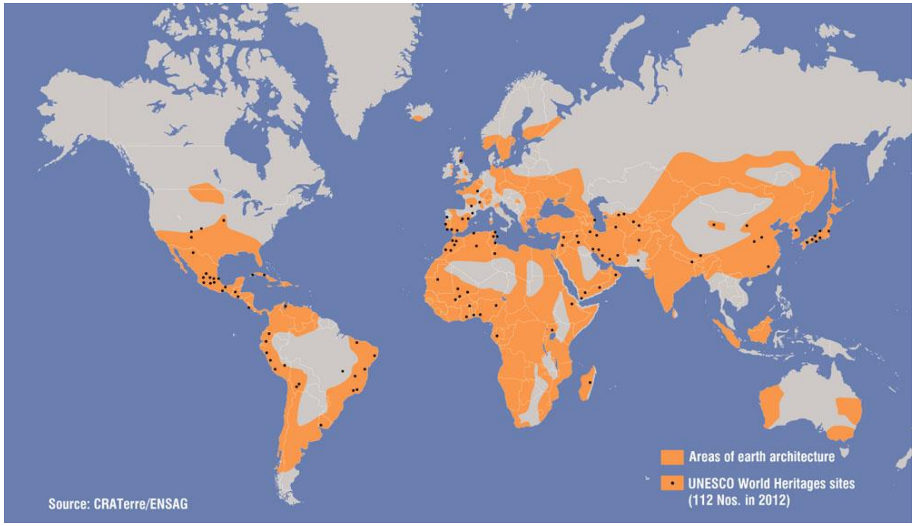
Outline

- Introduction and Background
- Research Updates on Earth Block Construction
  - Advancements in Finite Element Modeling
  - Use of Sugarcane Bagasse Fibers
- Preliminary Results on Wildfire Resilience
- Ongoing and Future Work
- Conclusions

Introduction (1)

- Earthen structures are structures built using mainly soil
- Most ancient and sustainable building technique (> 10,000 years old)
- 30%-50% of world's population currently lives in earth-based dwellings
- Earthen structures are found all over the world



Earth construction areas of the world (Source: CRATerre/ENSAG/Auroville)

City of Potosí in Bolivia (1600-2100 CE)

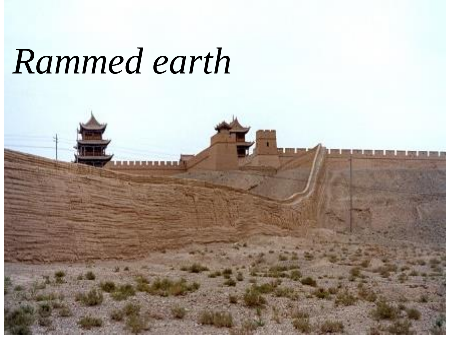
Pueblo de Taos, NM, USA (1000-1450 CE)

Great Mosque of Djenné in Mali (300 BCE)

Introduction (2)

- Cob
- Rammed earth
- Adobe
- Modern earth blocks
  - Compressed earth blocks (CEB)
  - Stabilized earth blocks (SEB)
  - Compressed and stabilized earth blocks (CSEB)

Cob



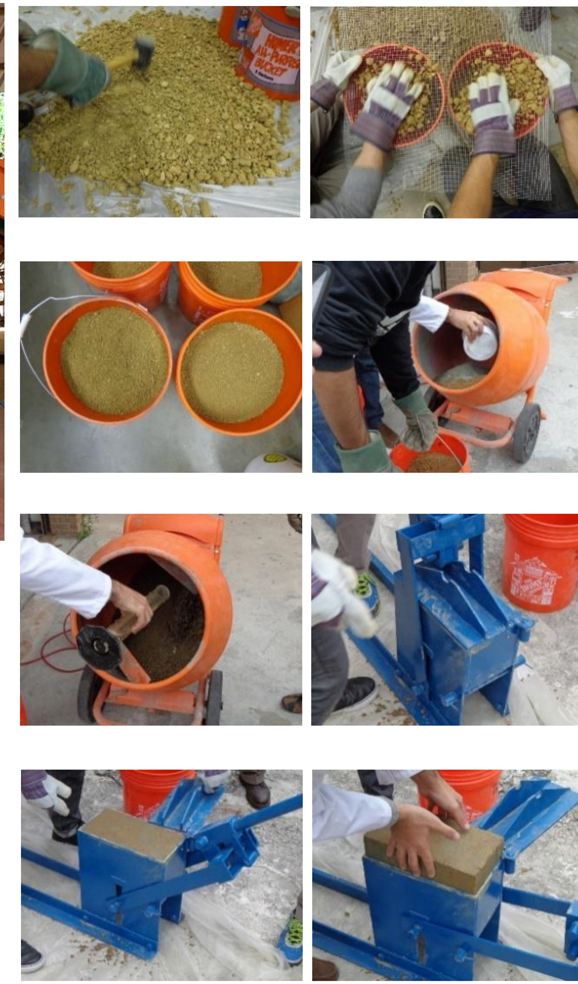
Rammed earth

Adobe

El Haj Yousif experimental school in Sudan (Adam, 2001)

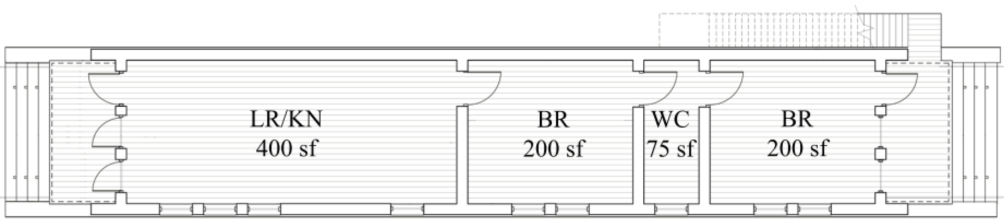
Earthen house in Davis, CA, USA (1955)

Compressed and Stabilized Earth Blocks (CSEB)



Fabrication process of CSEBs

Results from Previous Studies

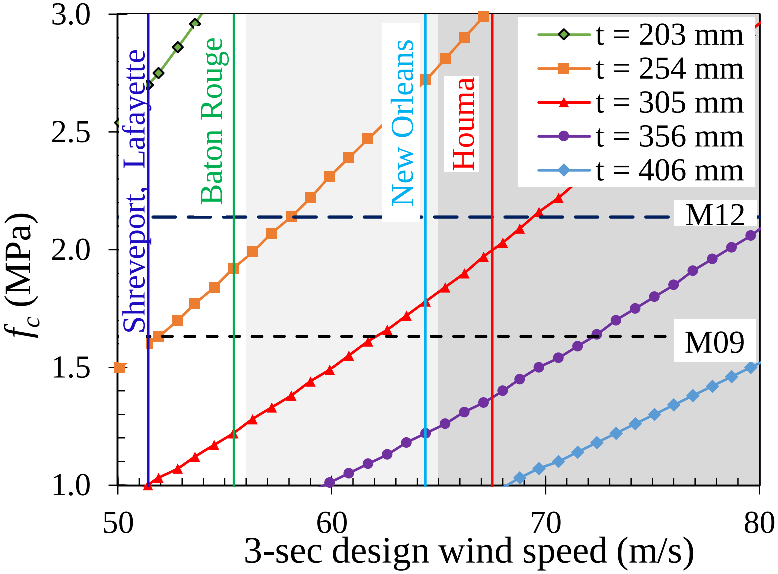


Floor plan

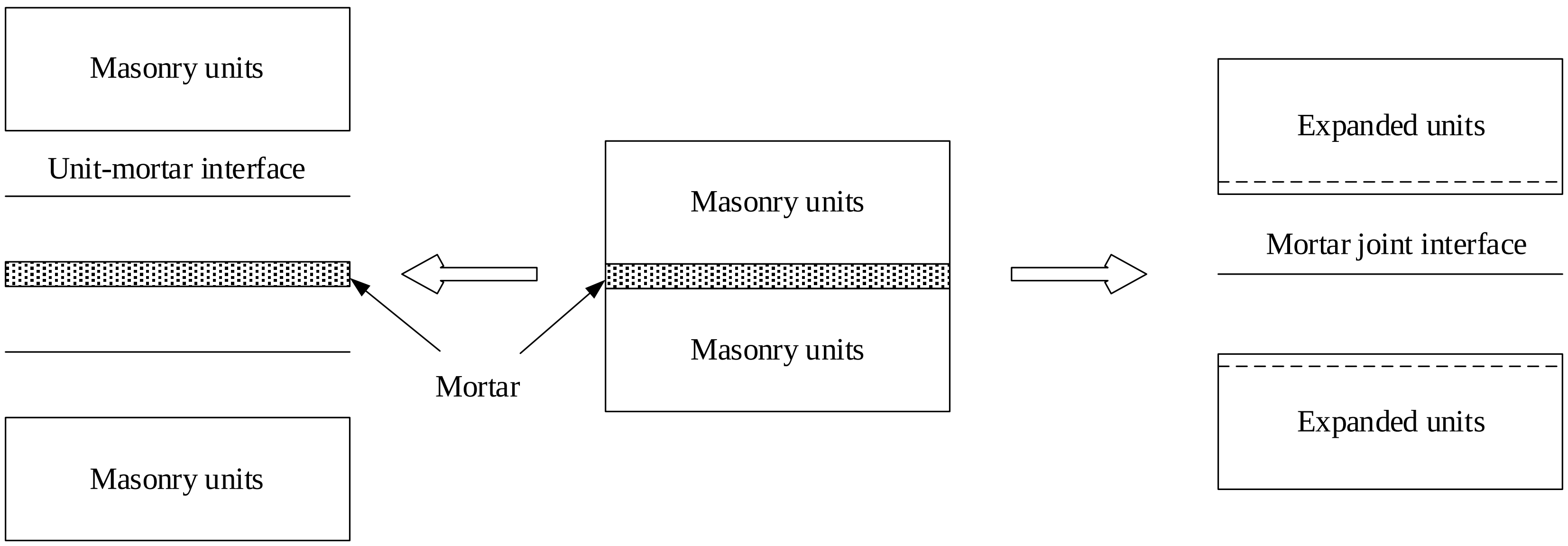
Front elevation

Rendering

Items	ICSEB Mortarless	Mortared CSEB	Light-frame Wood	Bricks	Concrete Blocks
Material ($)	7,186	6,676	15,638	19,533	12,844
Labor ($)	20,593	34,674	13,068	27,625	20,255
Overhead ($)	11,112	16,540	12,264	19,840	13,882
Total wall cost ($)	**38,891**	**57,890**	**40,970**	**66,997**	**46,981**

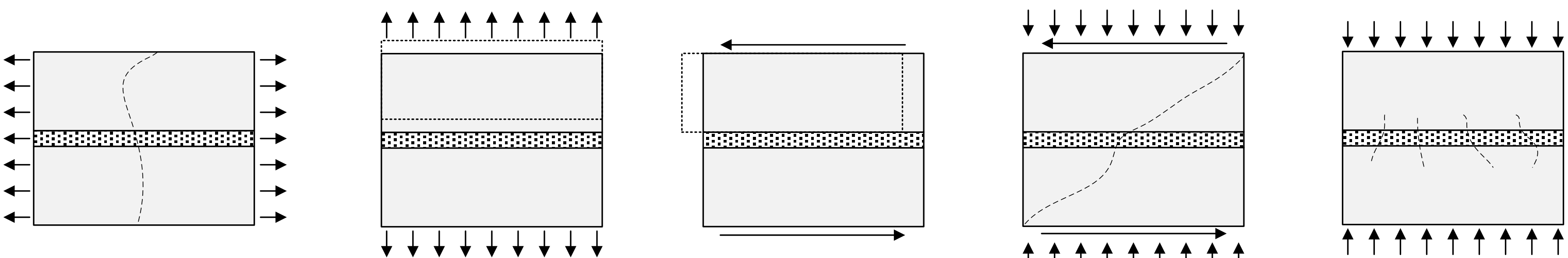


FE Micro-Modeling of Masonry (1)



Detailed micro-model (DMM)

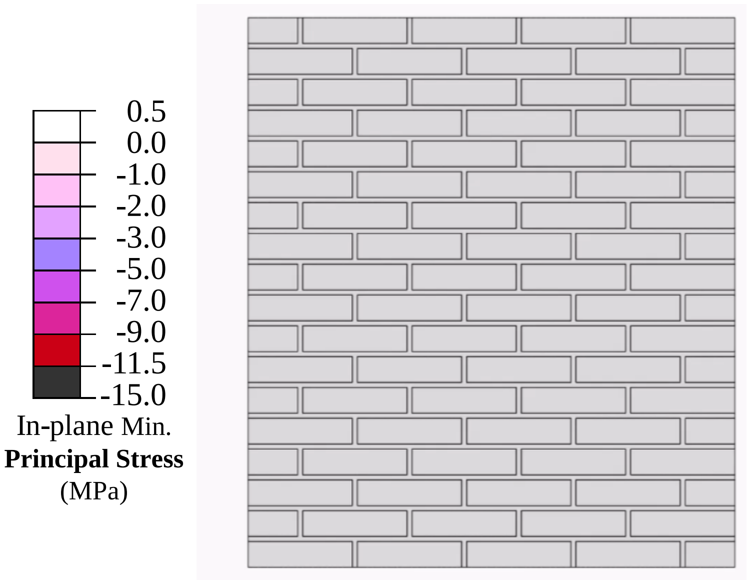
Simplified micro-model (SSM)

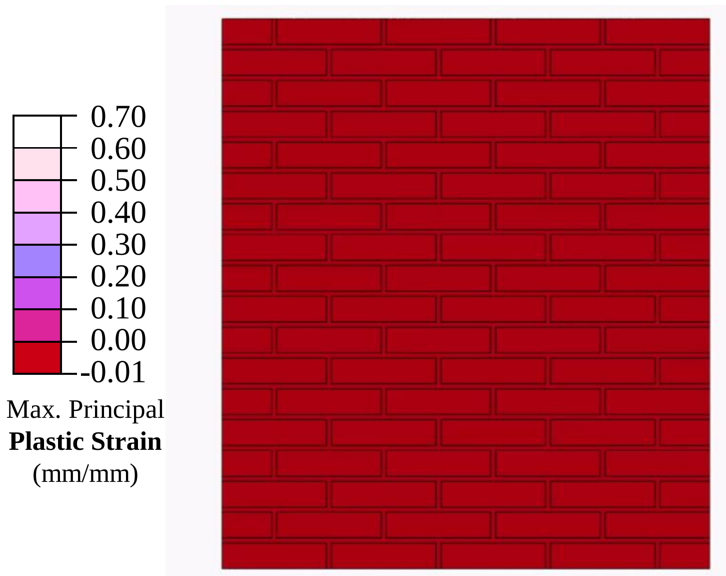


Block direct tensile cracking | *Joint tensile cracking* | *Joint slipping* | *Block diagonal tensile cracking* | *Masonry crushing*

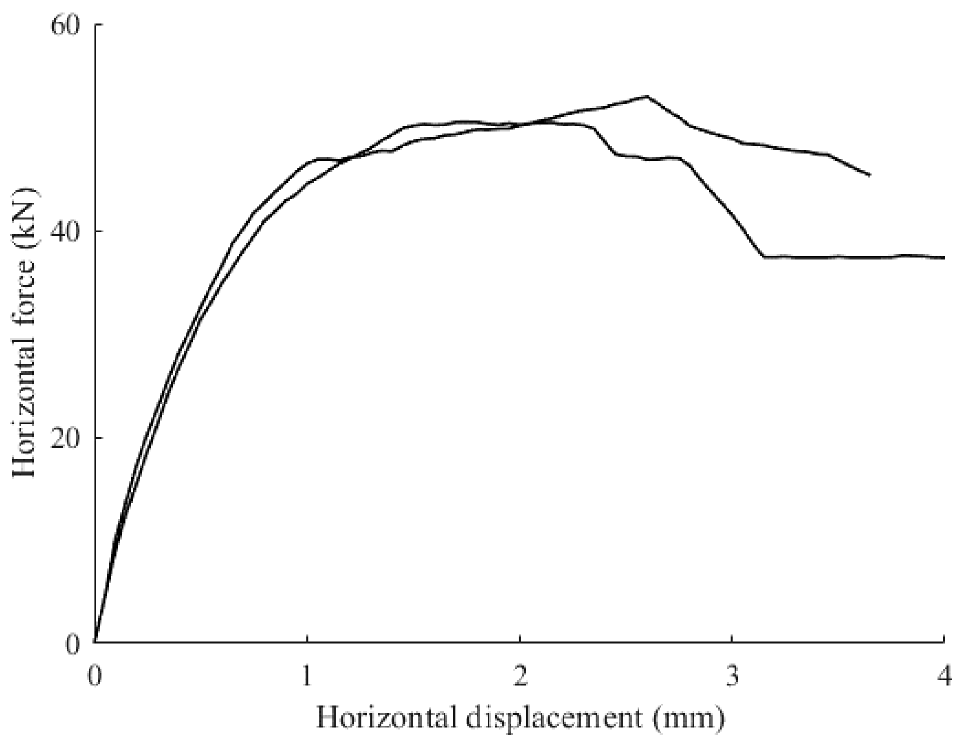
Masonry failure modes

FE Micro-Modeling of Masonry (2)



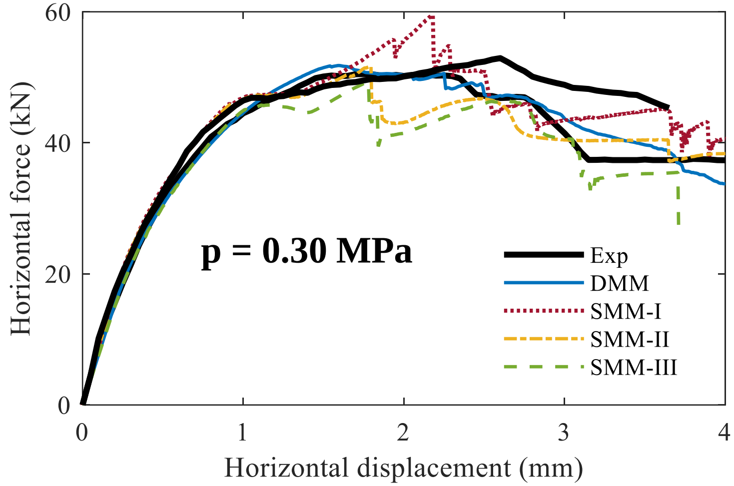


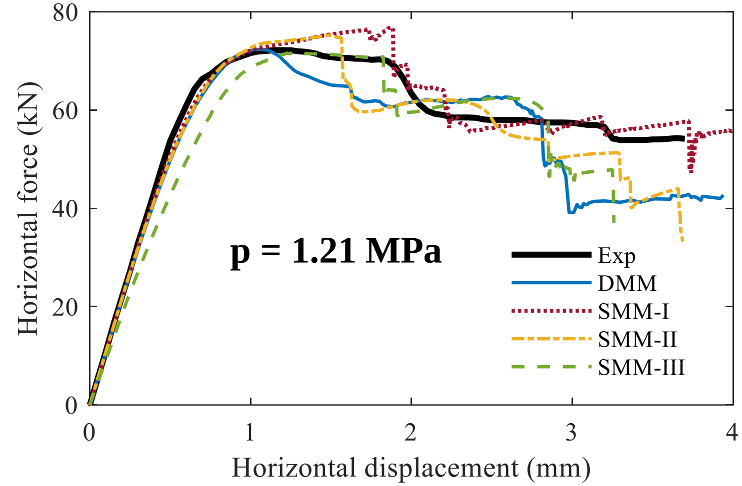
Validation of FE Response (DMM)

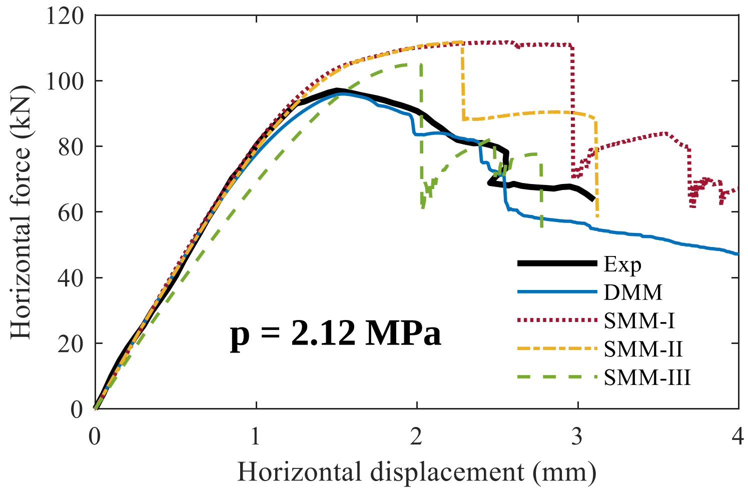


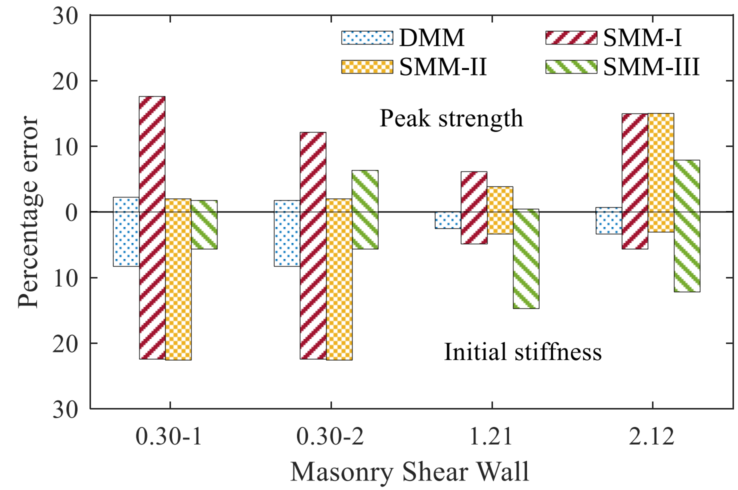
FE Micro-Modeling of Masonry (3)

Masonry Shear Walls: Experimental & FE response



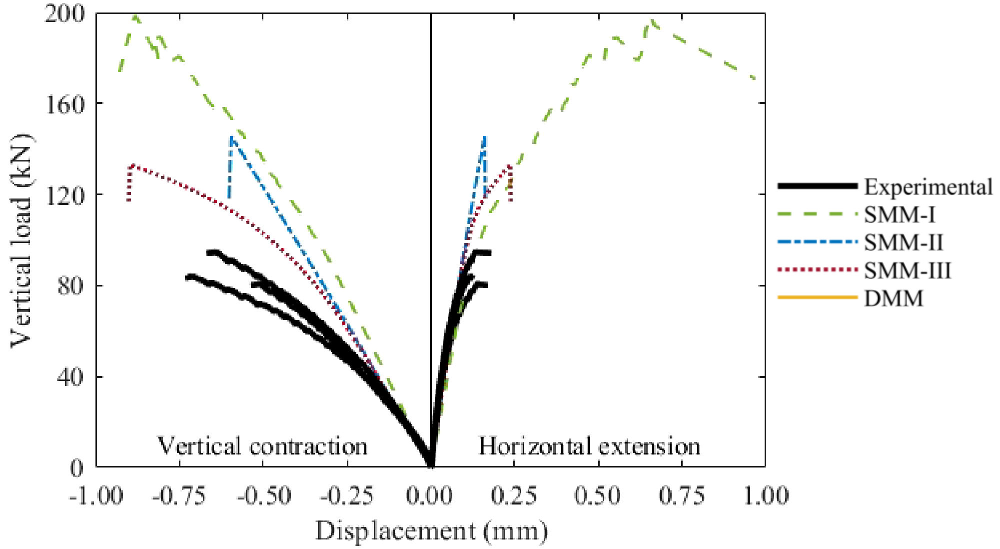




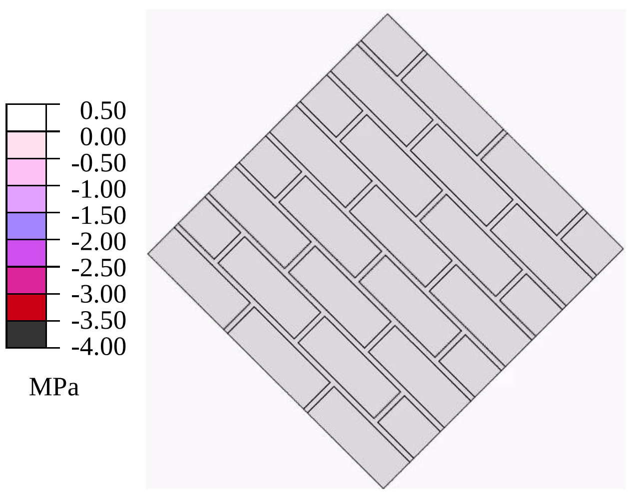


Percentage error in peak strength and initial stiffness

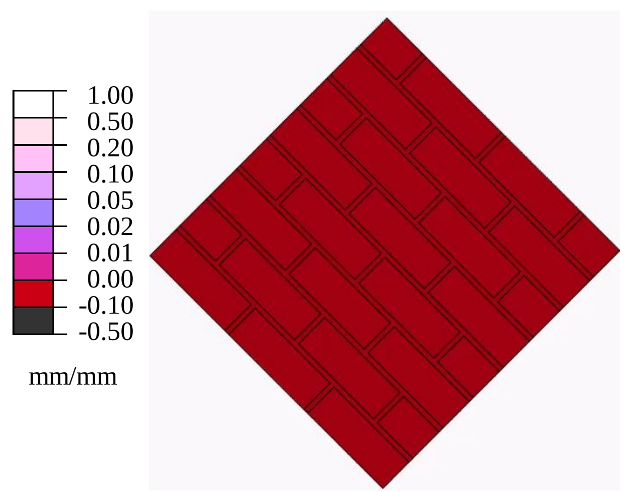
CSEB Masonry: FE responses



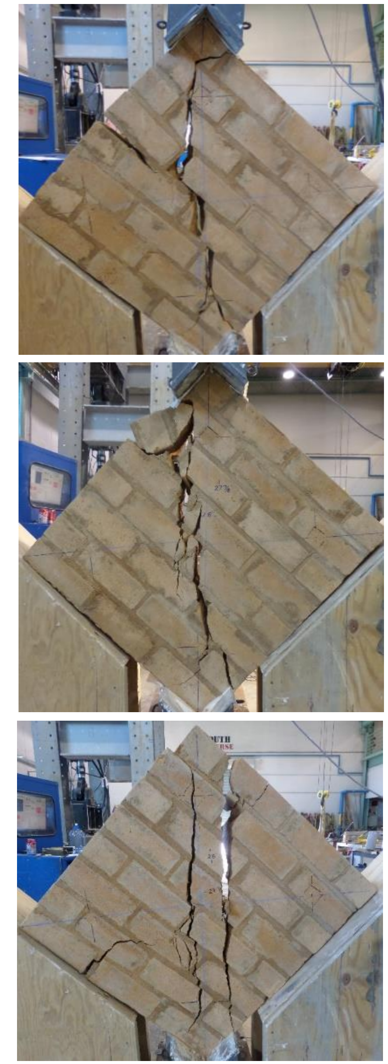
Comparison between experimental and FE responses for CSEB wallettes



In-plane minimum principal stress



In-plane maximum principal plastic strain



Experimental crack patterns
(MC Cuellar-Azcarate 2016)

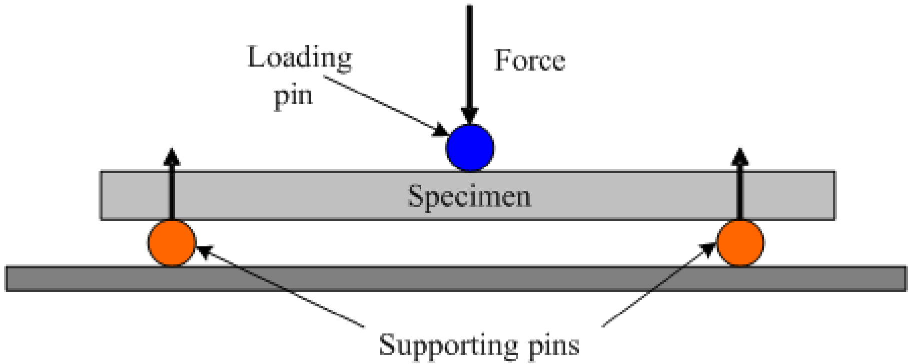
Use of Sugarcane Bagasse Fibers (SBF) in CSEBs

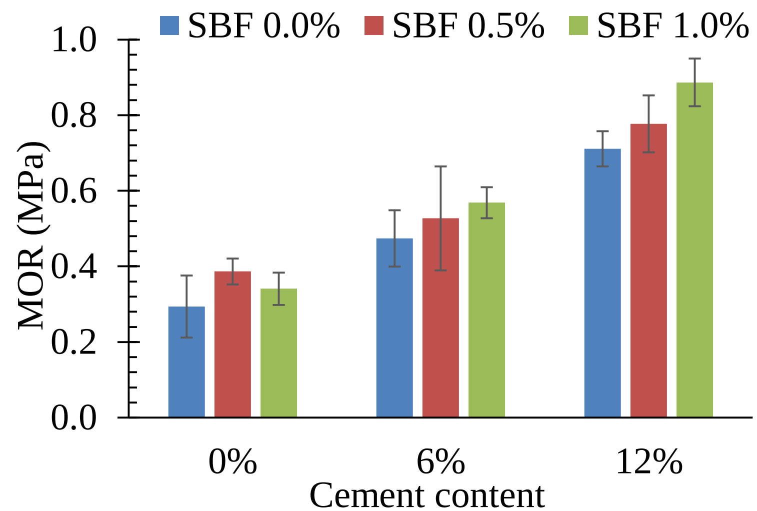
- Sugarcane production in 2018: 746.8 million metric tons (MMT) in Brazil, 376.9 MMT in India, and 108.7 MMT in China
  - > 400 million metric tons of SBF.
- USA sugarcane production in 2017: 28.0 MMT, mostly in Florida, Louisiana, and Texas,
  - ~ 9 million metric tons of SBFs.
- Brittle behavior of CSEBs can be improved using fibers

Sugarcane bagasse fibers

SBF stockpile in Alma Plantation, Louisiana

SBF-Reinforced CSEBs: Flexure Test



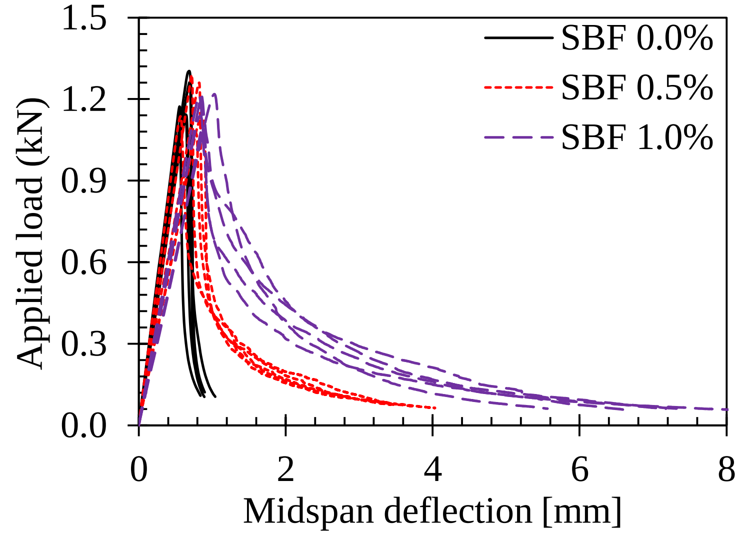


Unreinforced earth block

SBF-reinforced earth block

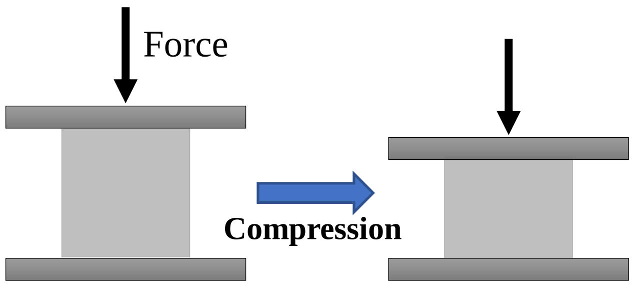
Crack pattern in unreinforced earth block

Crack pattern in SBF-reinforced earth block



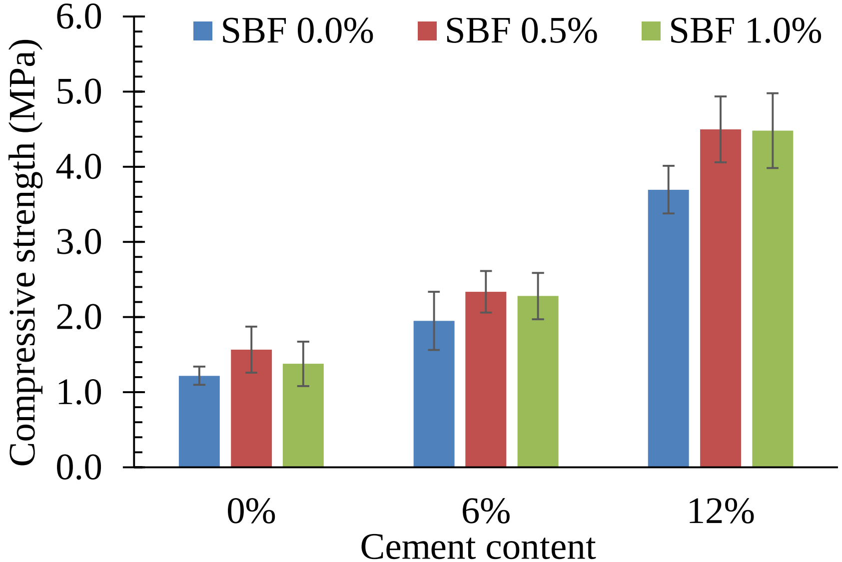
Earth block with 6% cement

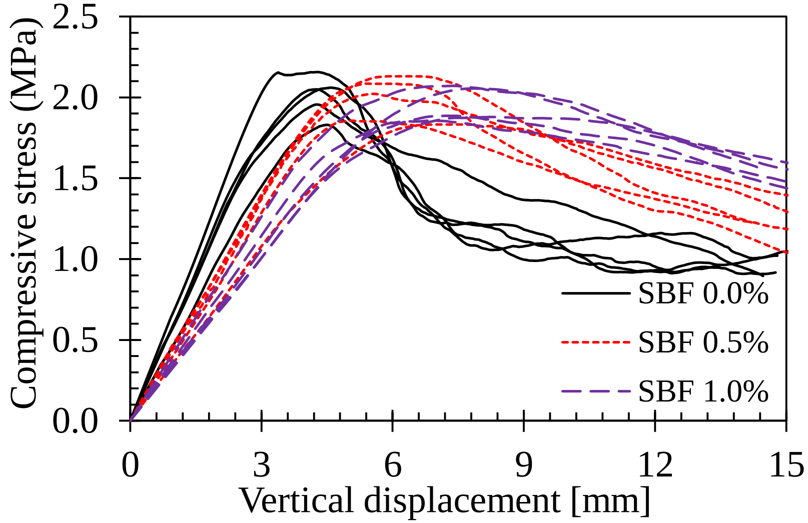
SBF-Reinforced CSEBs: Compression Test



Unreinforced earth block

SBF-reinforced earth block

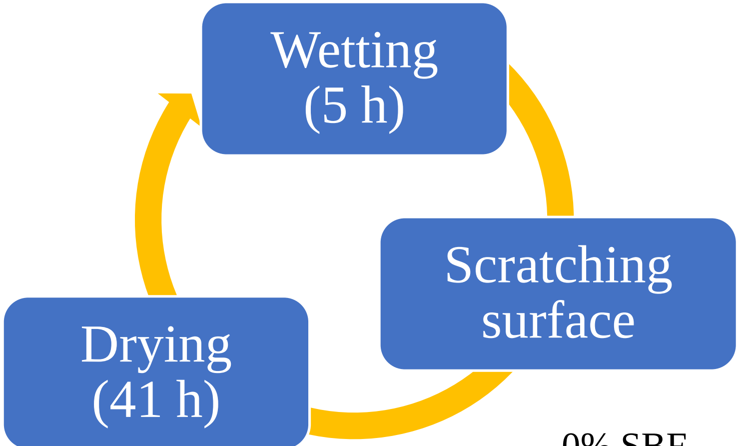




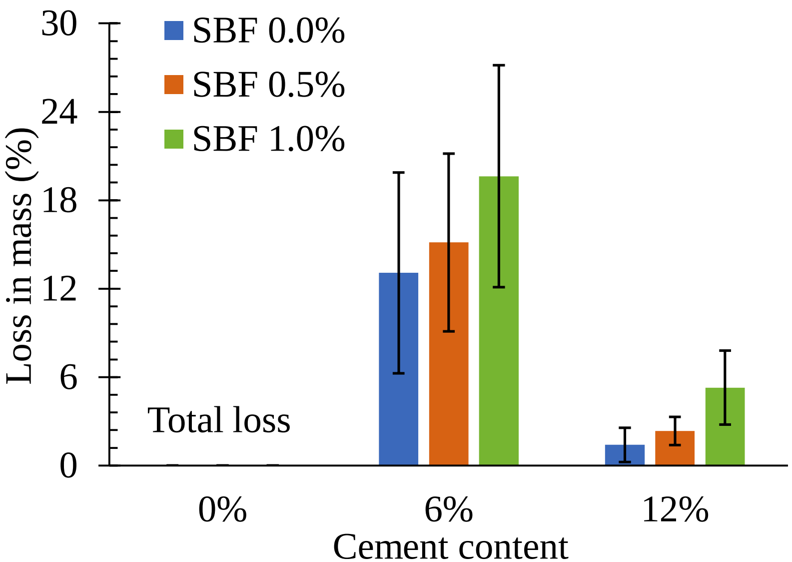
Earth block with 6% cement

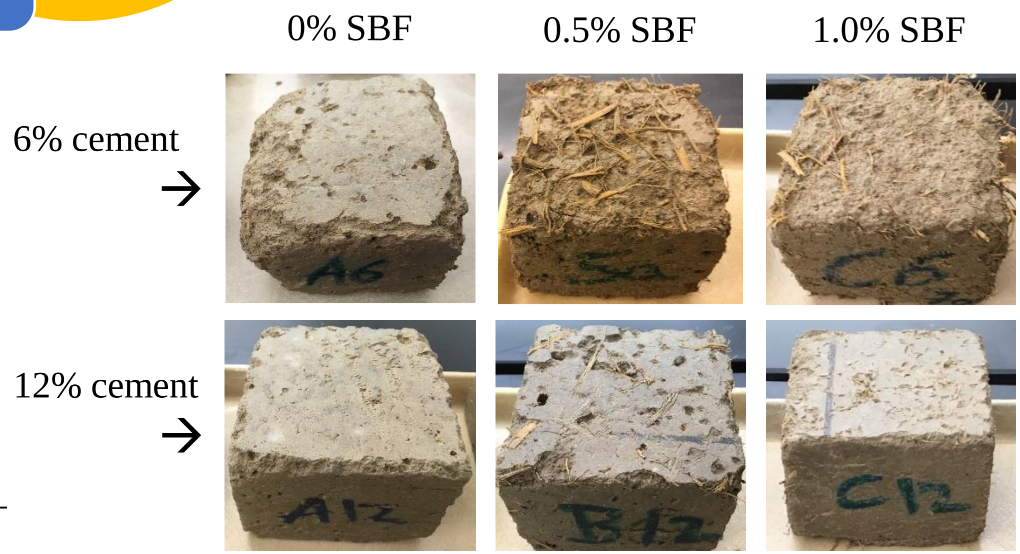
SBF-Reinforced CSEBs: Durability Test

Wetting and drying durability test



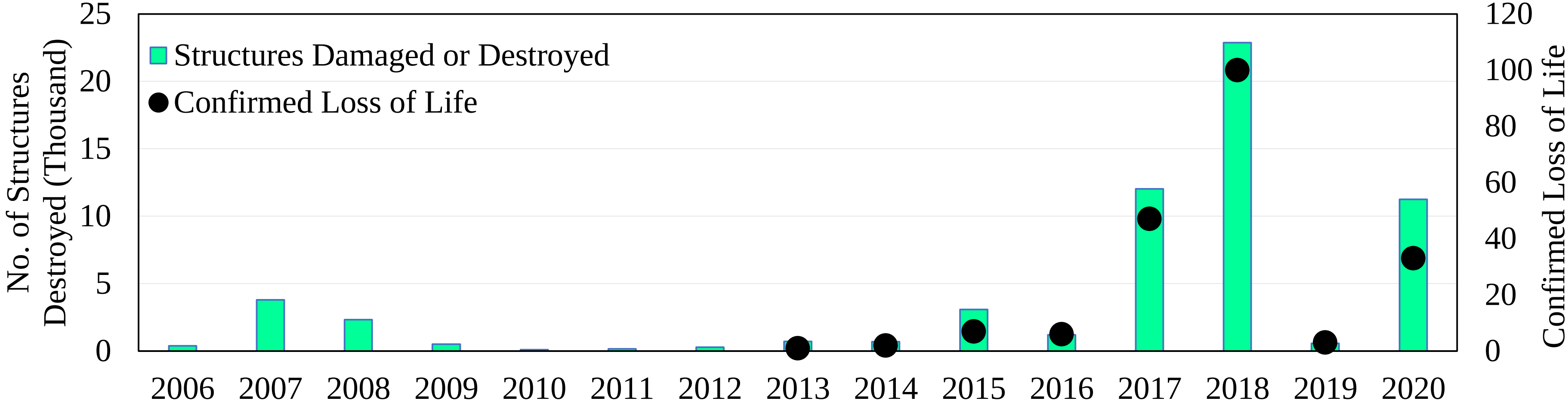
12 Cycles

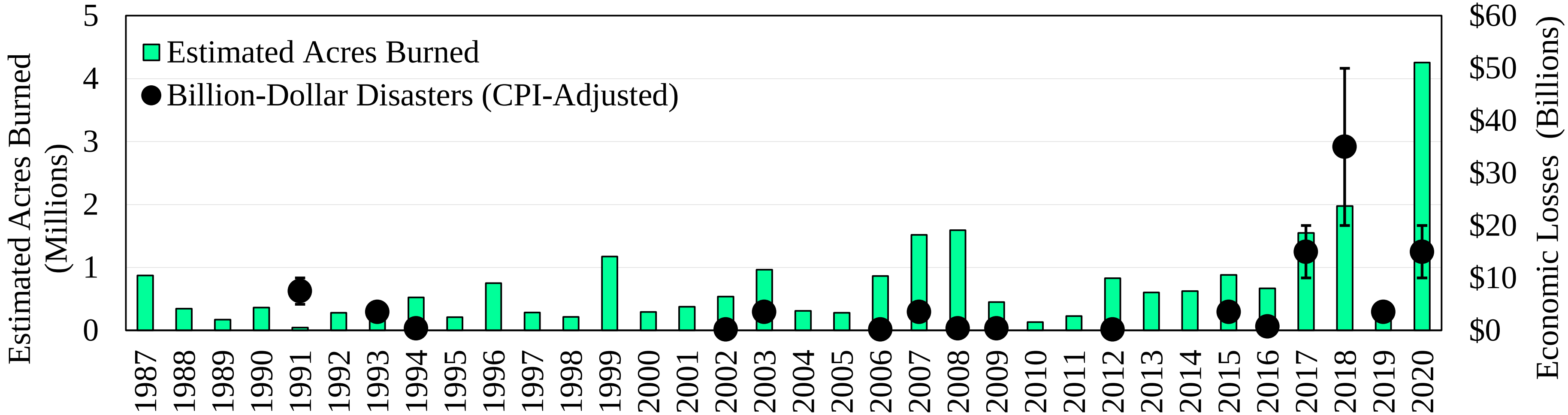




Specimens after durability test

California Wildfires History & Statistics



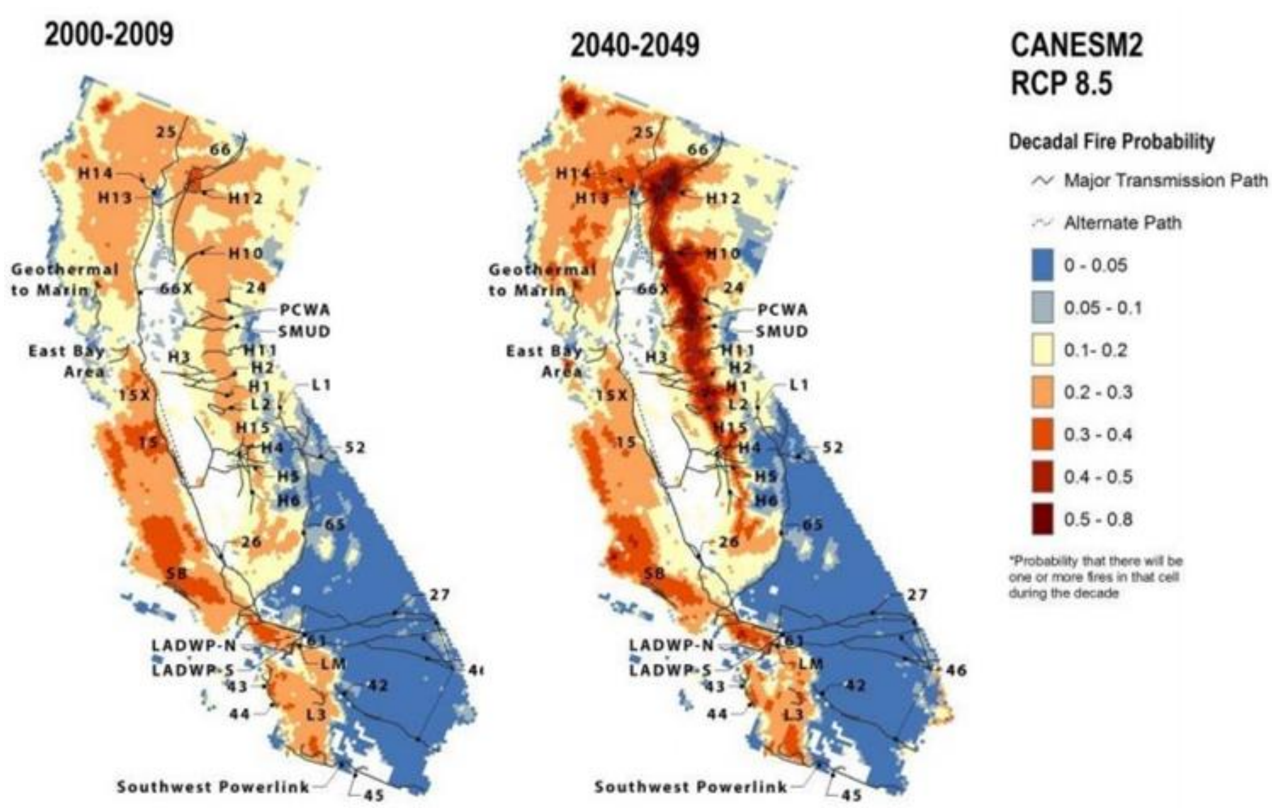


Data sources:

1. Estimated acres burned and confirmed loss of life: https://www.fire.ca.gov/incidents/
2. Damaged/destroyed structures: https://headwaterseconomics.org/natural-hazards/structures-destroyed-by-wildfire/
3. Economic losses: https://www.ncdc.noaa.gov/billions/time-series/CA

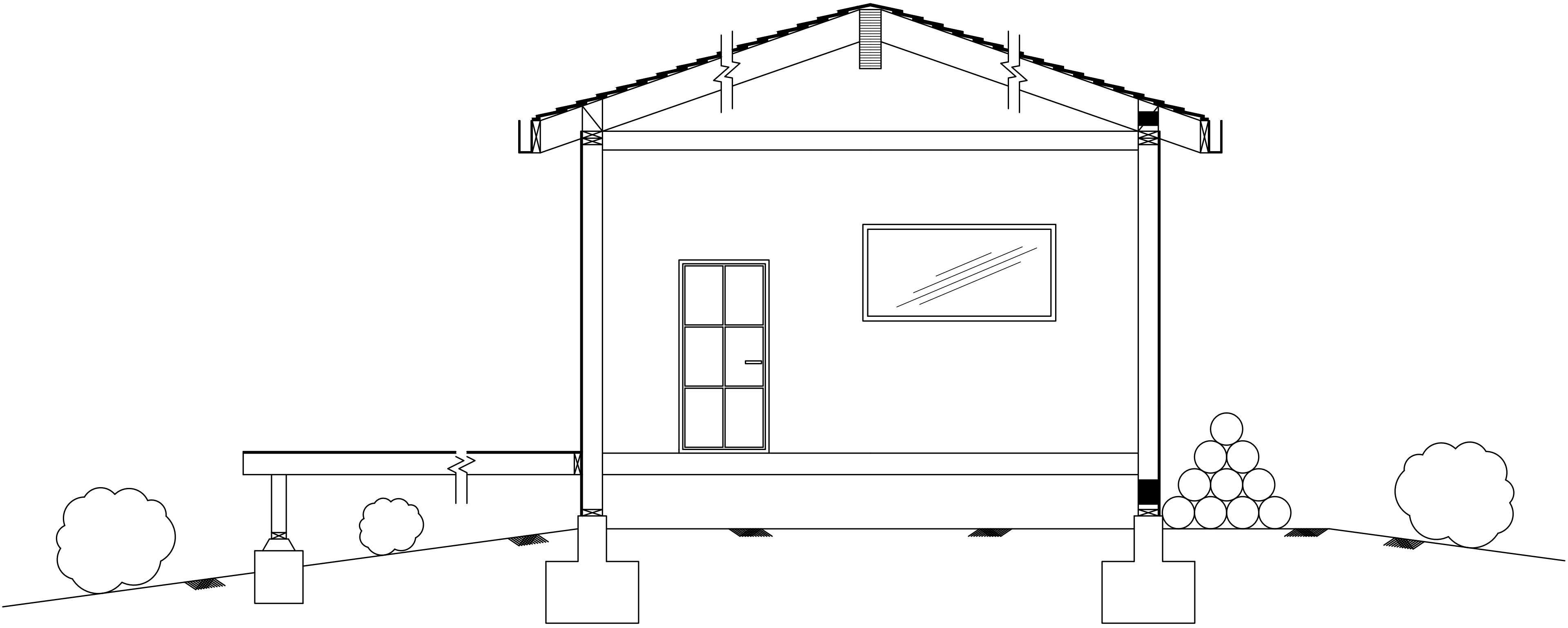
Effect of Climate Change on Wildfire Hazard

➢ Rising global temperatures are increasing the severity of wildfires across the western United States (Westerling 2018: CEC Report No. CCCA4-CEC-2018-014)



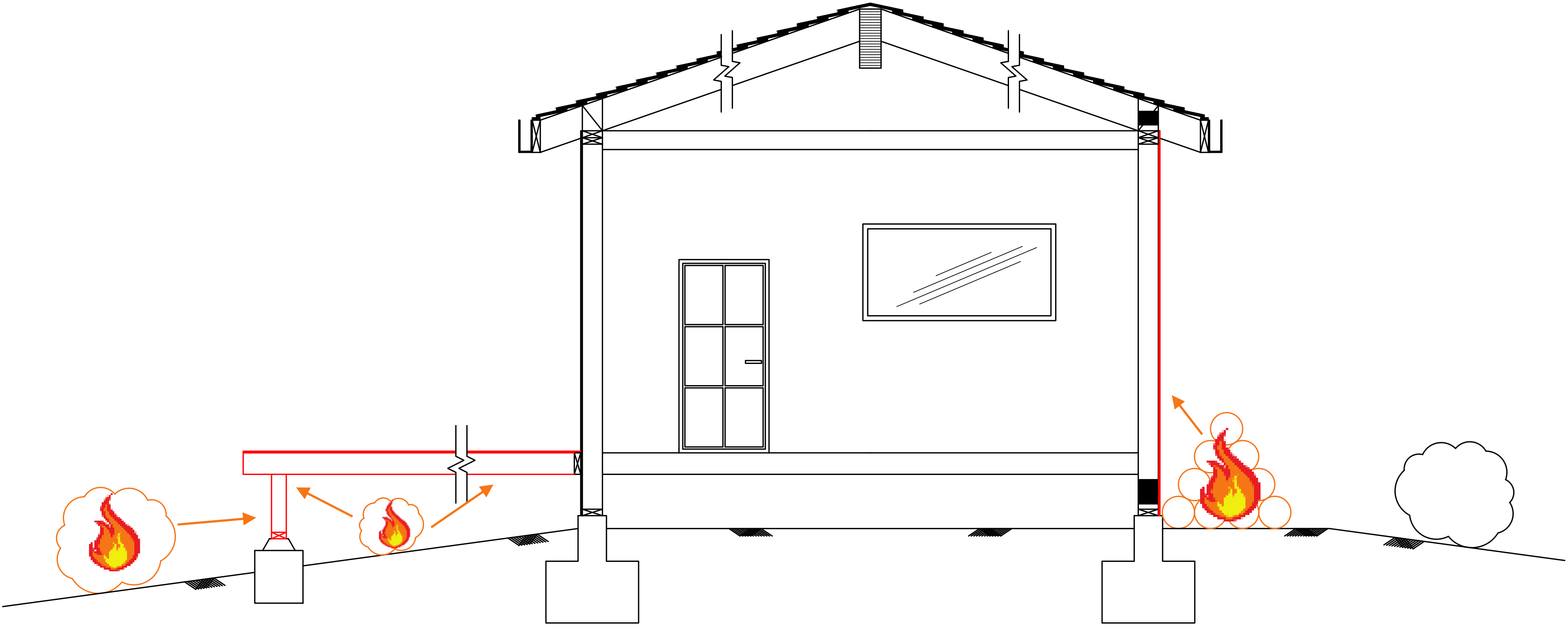
Wildfire simulations for California's fourth climate change assessment projecting changes in extreme wildfire events with a warming climate

Ignition Mechanisms



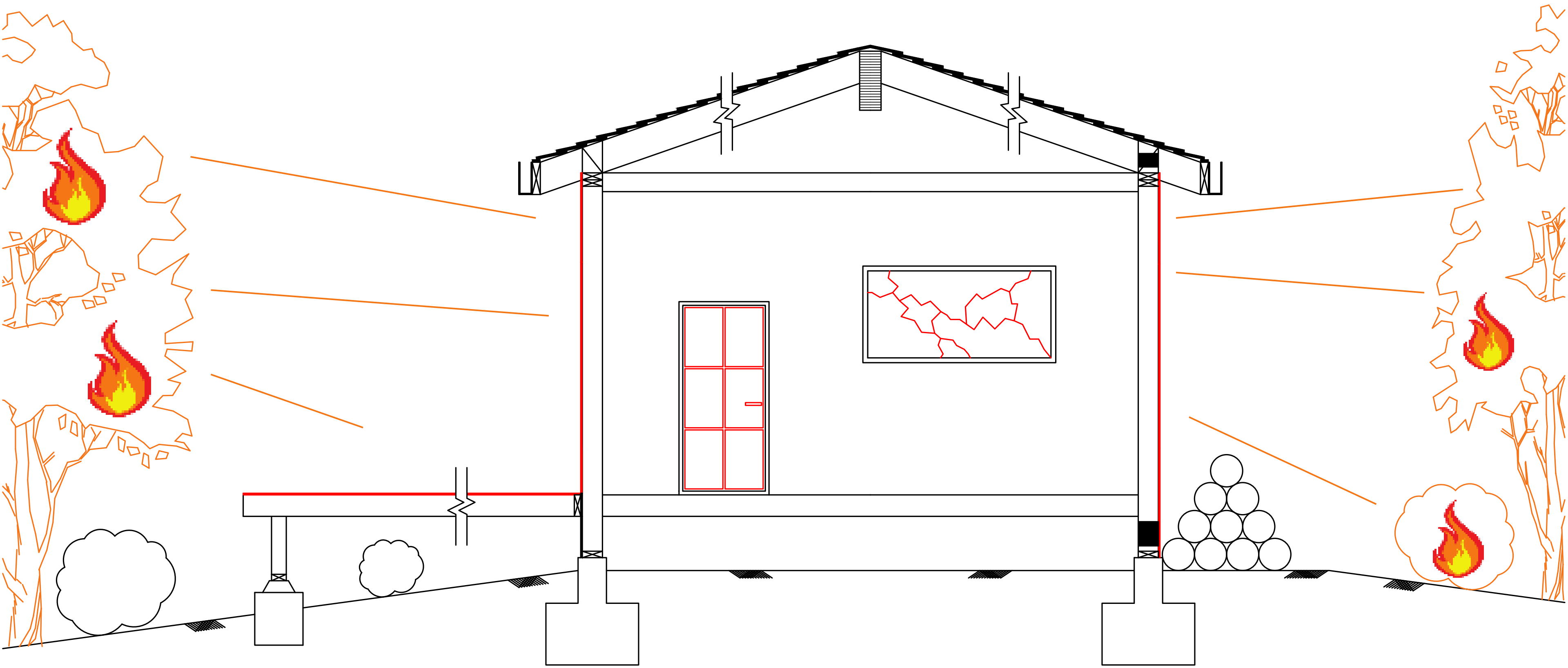
Ignition Mechanisms

- Direct contact with flames/surface fires



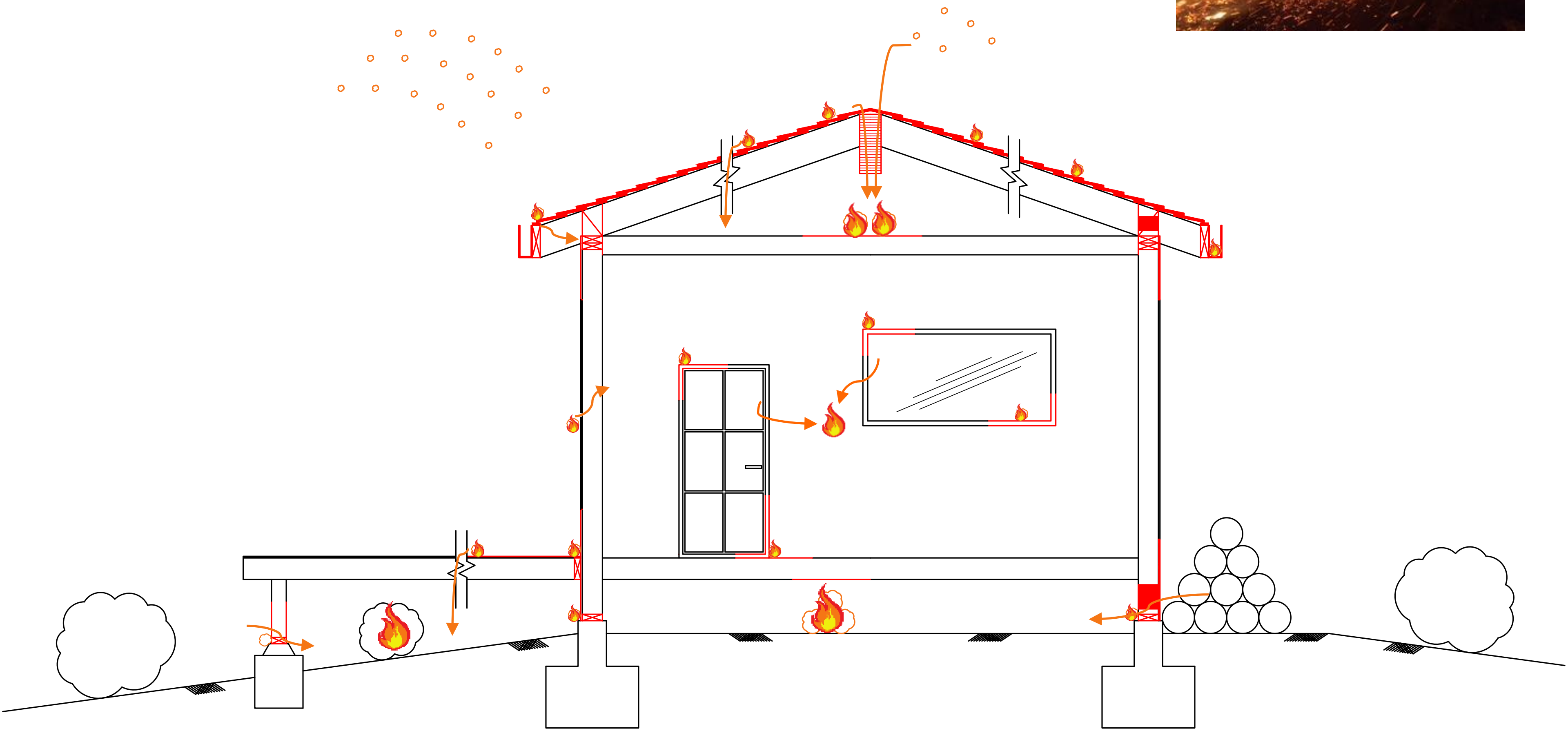
Ignition Mechanisms

- Heat radiation/crown fires



Ignition Mechanisms

- Ember attacks/firebrands

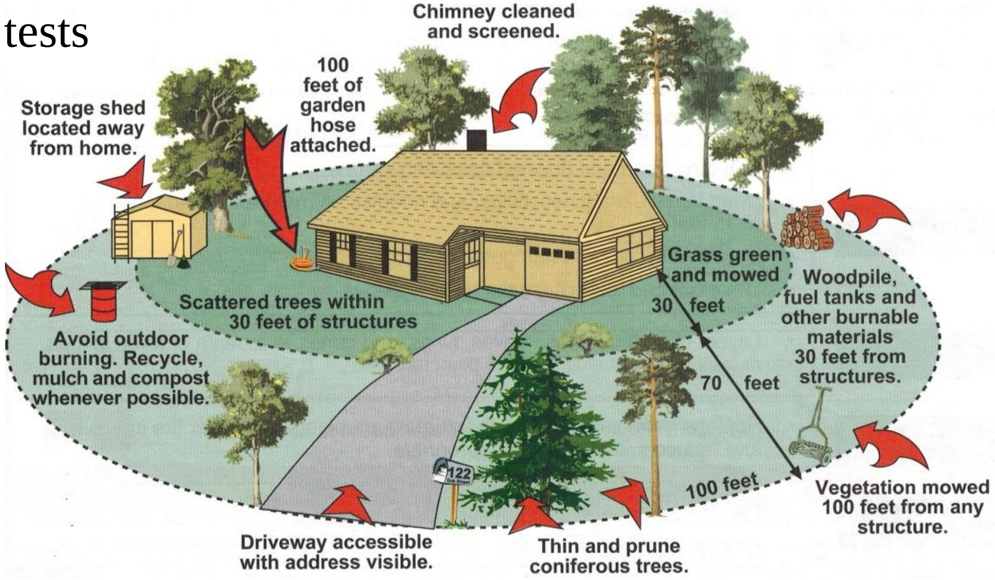


California Building Code for WUI (Ch. 7A)

- Fire Resistance Test Standards
  - **Exterior wall siding/sheathing**: 150-kW direct flame exposure for 10 minutes
  - **Exterior windows**: 150-kW direct flame exposure for 8 minutes
  - **Decking**: under-deck exposure to 80-kW intensity direct flame for 3 minutes.
  - **Roof**: comply with various requirements (for coverings, valleys, and gutters) of Chapter 7A and Chapter 15 of California Building Code
  - **Horizontal projection underside**: 300-kW direct flame exposure for 10 minutes
  - **Other ignition-resistant materials** (e.g., fire-retardant-treated wood): 30-minute ASTM E84 or UL 723 tests

- Exterior Protection

- Defensible Space (5’, 30’, 100’)

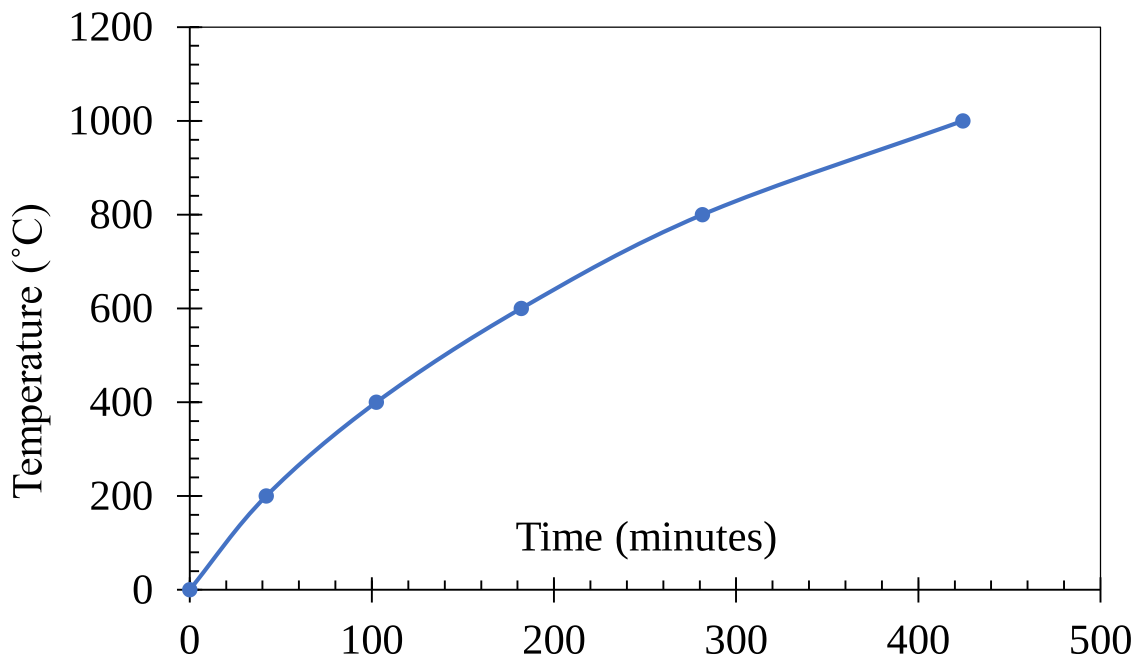


CSEB Construction: Fire Resistance

CSEB Materials

Laboratory tests	Standards	Properties	Values
Particle-size analysis	ASTM D6913-04 D7928-16	Gravel (>2 mm) (%)	<1.00
		Sand (2–0.063 mm) (%)	61.05
		Silt (0.063–0.002 mm) (%)	27.10
		Clay (<0.002 mm) (%)	11.86
Atterberg limits	ASTM D4318-10	Liquid limit LL (%)	32.00
		Plastic limit PL (%)	21.35
		Plasticity index PI (%)	10.65
Soil compaction tests	ASTM D698-12	Optimum moisture content (%)	20.16
		Maximum dry density (kg/m^3)	1711.8
		Specific gravity of soil (-)	2.59

CSEB High Temperature Test



CSEB Specimens After High Temperature Test

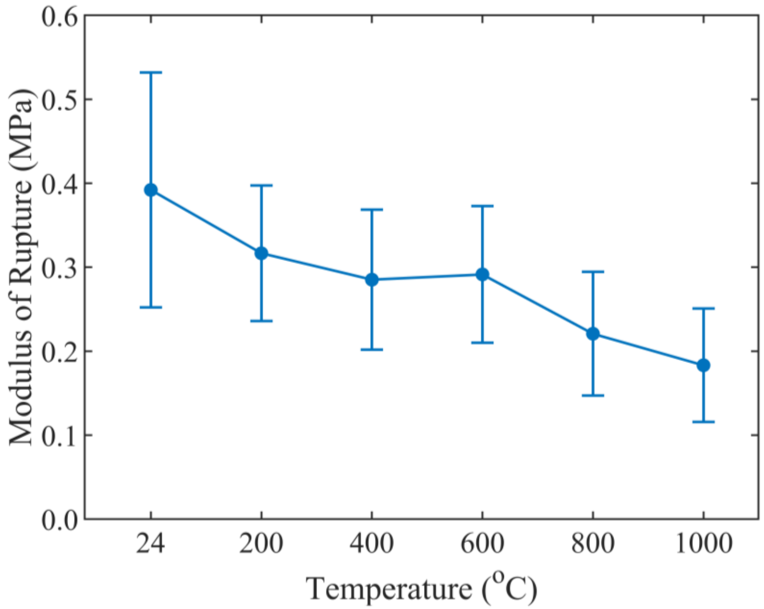
CSEB specimens (left to right): 24±2°C, 200 °C, 400 °C, 600 °C, 800 °C, 1000 °C.

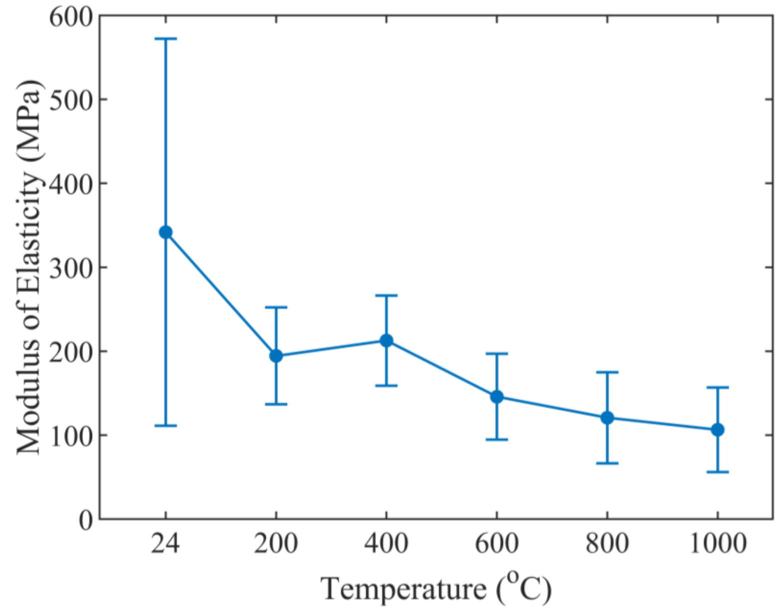
24±2°C | *200 °C* | *400 °C* | *600 °C* | *800 °C* | *1000 °C*

CSEB Flexure Test Results

Temperature	Modulus of Rupture		Modulus of Elasticity	
	Mean (MPa)	COV (%)	Mean (MPa)	COV (%)
24±2 °C	0.392	35.7	341.8	67.4
200 °C	0.317	25.5	194.5	29.6
400 °C	0.285	29.2	212.7	25.3
600 °C	0.291	28.0	145.7	35.1
800 °C	0.221	33.4	120.8	44.9
1000 °C	0.183	36.9	106.5	47.3

CSEB Flexure Test Results

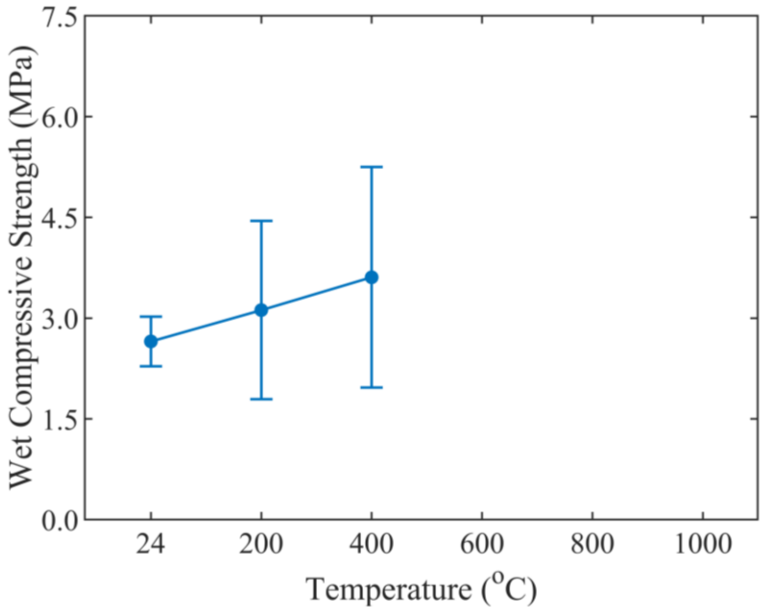


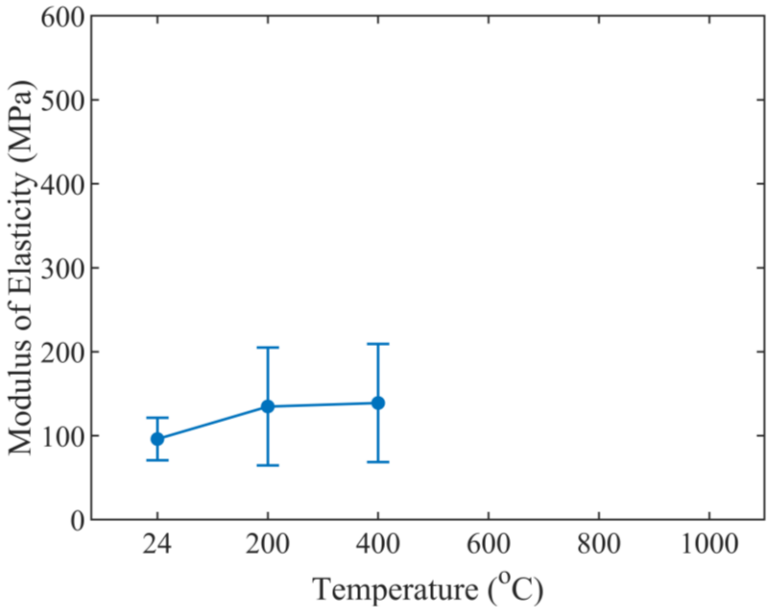


CSEB Compression Test Results

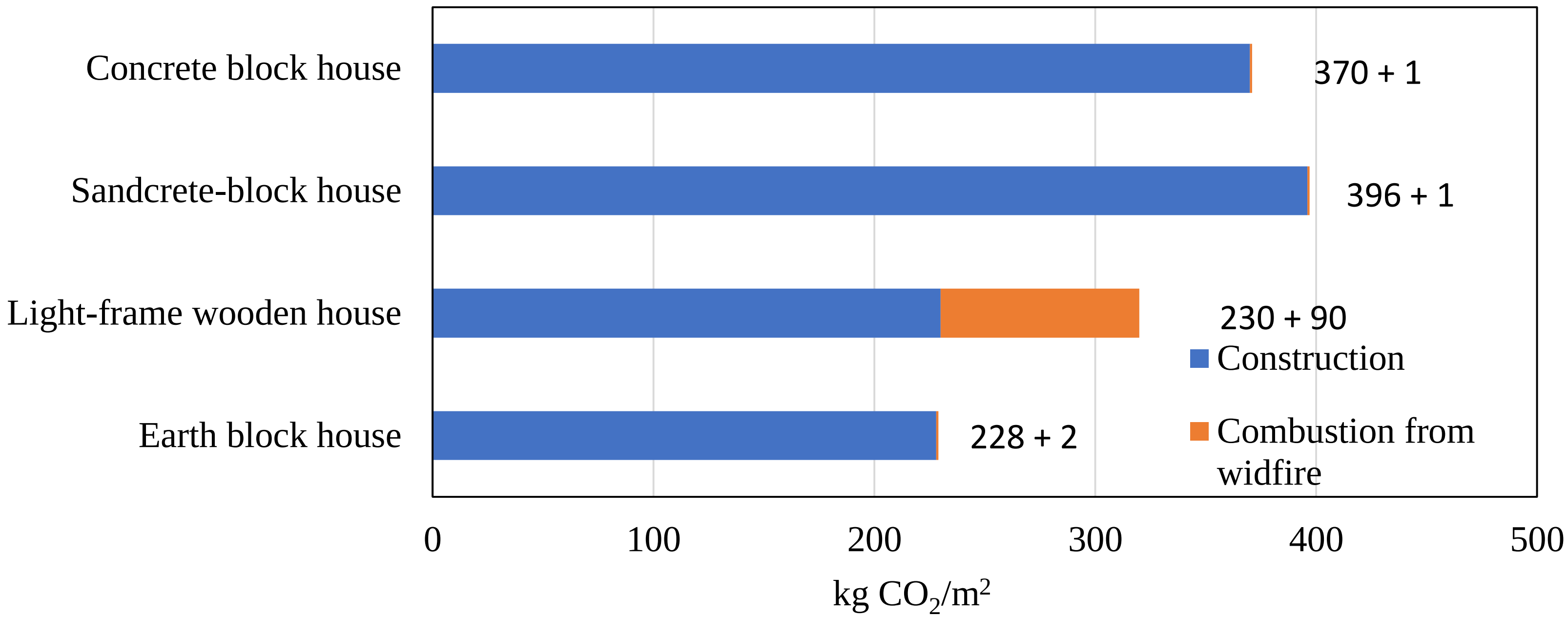
Temperature	Wet Compressive Strength		Modulus of Elasticity	
	Mean (MPa)	COV (%)	Mean (MPa)	COV (%)
24±2 °C	2.654	13.9	96.0	26.3
200 °C	3.120	42.6	134.8	52.1
400 °C	3.608	45.5	139.0	50.5
600 °C	-	-	-	-
800 °C	-	-	-	-
1000 °C	-	-	-	-

CSEB Compression Test Results





Ongoing and Future Work



- Complete experimental testing under uniform heating.
- Experimental testing under gradient temperature (ASTM E119).
- Thermal properties (energy savings + wildfire indoor temperature).
- Evaluation of emissions under wildfire conditions (individual house and community level).

Conclusions

- Earthen masonry represents an affordable, safe, and sustainable technique for construction of houses and low-rise buildings
- Finite element modeling using detailed micro-models is an accurate tool to predict mechanical behavior
- Natural fibers can be effectively used to improve the ductility
- Research is ongoing to develop an affordable fire-resistant construction technique based on CSEBs
- Earthen masonry shows great potential to address climate change and equitable economic development
- Future research will focus on wildfire resilience and mitigation of wildfire smoke emissions

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Thank you
Questions?

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