Creating a Roadmap to Adoption of High Strength Steel in Structural Masonry

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Dimitrios Kalliontzis
Assistant Professor
University of Houston

Collaborators:
Omar Khalid, MSc Student, University of Houston
Waleed Khan, PhD Student, University of Houston

THE MASONRY SOCIETY

A Brief History

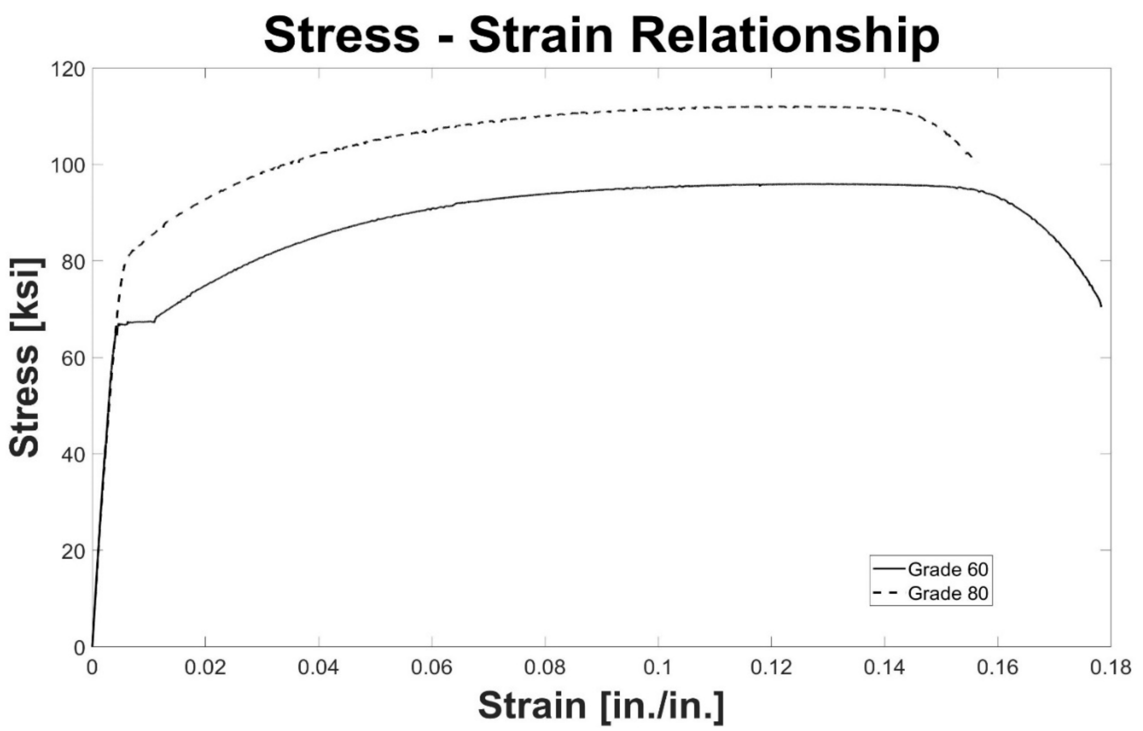
- **1900s** — Grades 33, 40, 50 Common usage
- **1959** — Grades 60,75 ASTM A432, A431
- **1963** — **Grade 60 Allowed by ACI 318**
- **1968** — Grades 40,60 & 75 ASTM A615 Deformed bars
- **2001** — Grade 75 ASTM 955
- **2004** — Grade 100 ASTM 1035
- **2005** — Grade 100 ACI 318 Confinement RF Non-Seismic
- **2007** — Grades 75,100,120 ASTM 1035 & ACI 318
- **2008** — Grade 100 ASTM 318 - Seismic Confinement Reinforcement
- **2009** — Grade 80 ASTM A615, A706
- **2011** — **Grade 80 ACI 318**

*There is a continuing trend of **increasing** availability of r/f of **higher grades** by the steel industry*

Motivation

❑ Why high-strength steel?

- Gain in member strength
- Reduce steel congestion
- Reduce material and construction cost
- Reduce building carbon footprint
- (Some reduction in ductility)



Broaden masonry design options *that are available to engineers*

Improve competitiveness *of structural masonry*

Current Usage in ACI 318-19

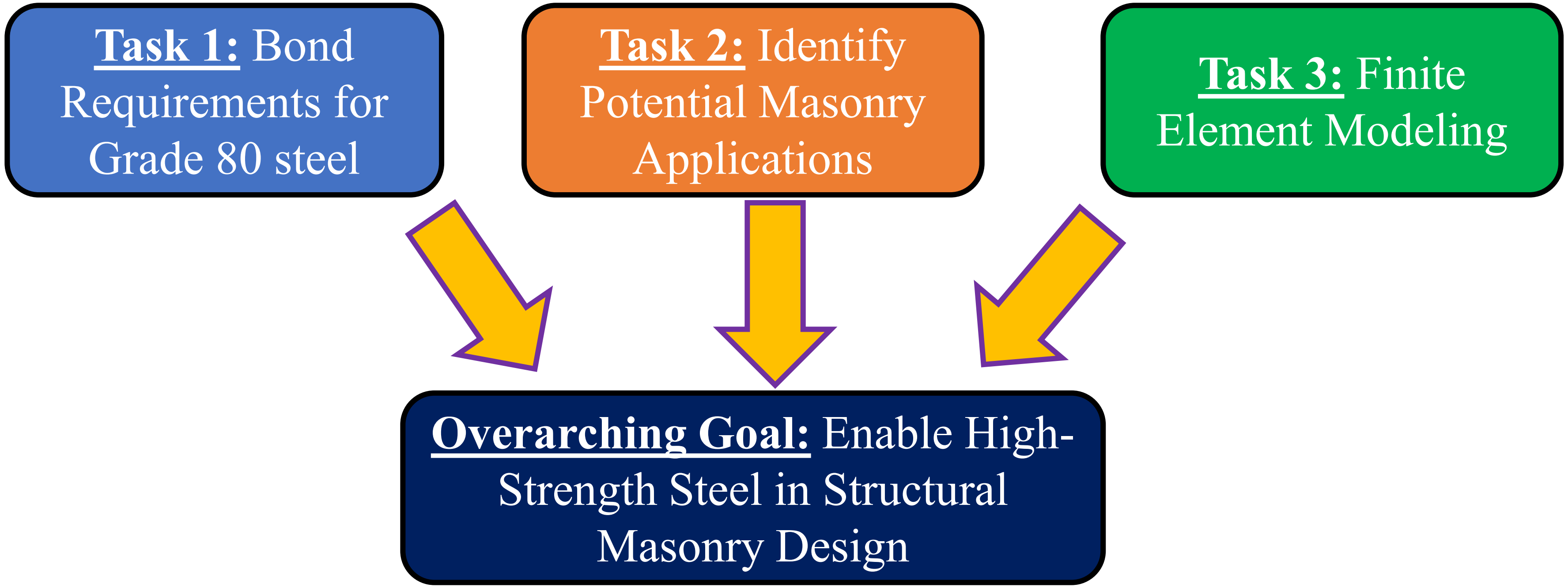
Usage	Application		Maximum value of f_y permitted for design calculations, psi
Flexure; axial force; and shrinkage and temperature	Special seismic systems	Special moment frames	**80,000**
		Special structural walls	**100,000**
	Other		**100,000**
Lateral support of longitudinal bars; or concrete confinement	Special seismic systems		**100,000**
	Spirals		**100,000**
	Other		**80,000**
Shear	Special seismic systems	Special moment frames	**80,000**
		Special structural walls	**100,000**
	Spirals, shear friction, stirrups, ties, hoops		60,000
Torsion	Longitudinal and transverse		60,000

Practically no available research on structural masonry

Research Plan

❑ Current Restrictions in TMS 402:

- Maximum allowable stress: 32,000 psi with reference to Grade 60 steel r/f [*TMS 402-16, 8.3.3.1*]
- Maximum strength: 60,000 psi [*TMS 402-16, 9.1.9.3*]
- See also [*TMS 402-16, 11.1.8.6*]



Experimental Program Design

❑ What are the development length requirements for **Grade 80** bars in masonry?

$$l_d = \frac{0.13 d_b^2 f_y \gamma}{K\sqrt{f'_m}}$$ TMS 402-16

f_y= yield strength

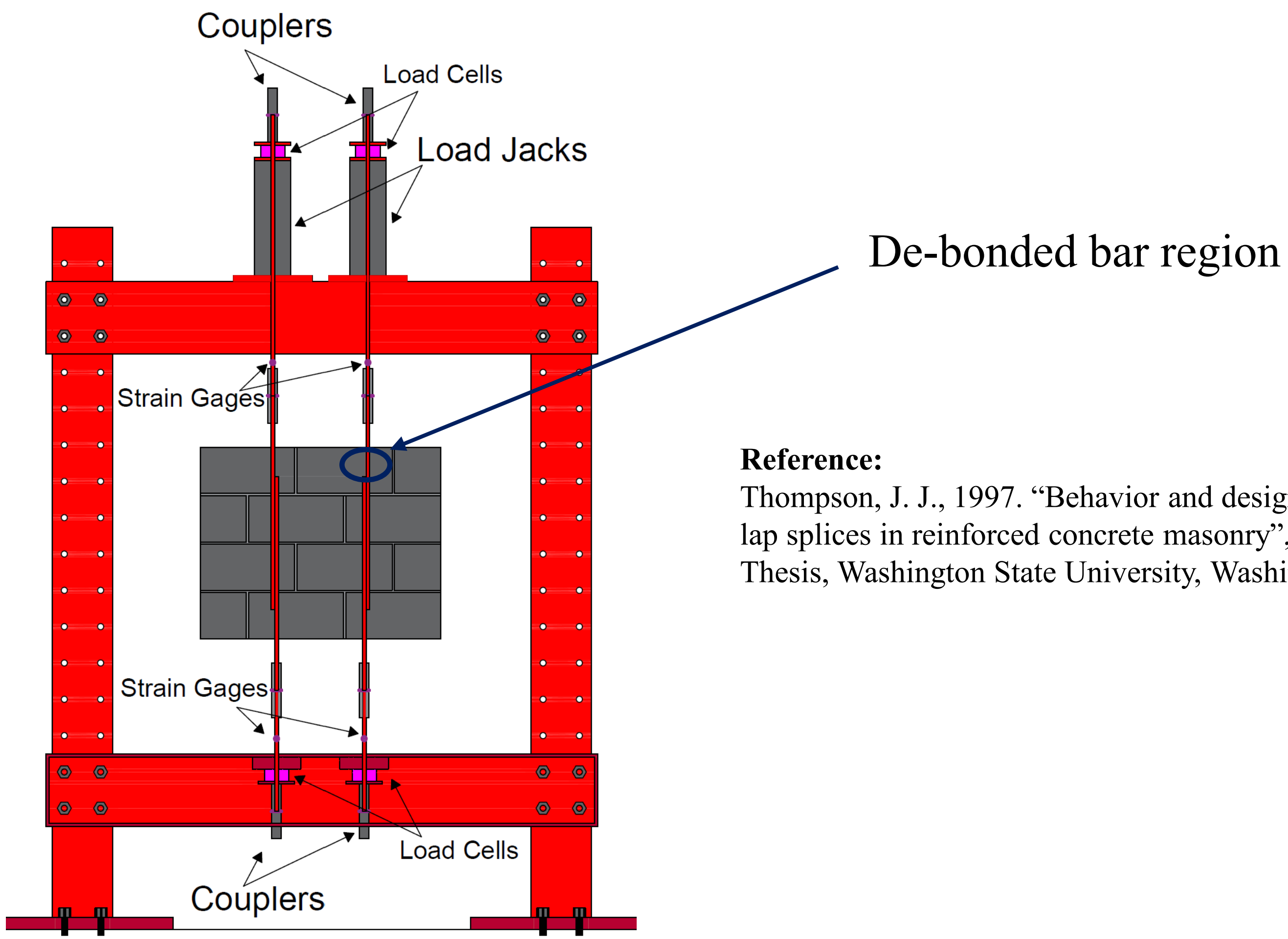
d_b= bar diameter

γ= factor accounting for bar size

K= factor accounting for cover/spacing to bar

*+ Consideration to **1.15 (Grade 80)** and **1.3 (Grade 100)** factors applied to high-strength steel in ACI 318-19*

$$e.g., l_{d,Grade\ 80} = \mathbf{1.15} \times \left[\frac{0.13 d_b^2 f_y \gamma}{K\sqrt{f'_m}}\right]$$



Reference:
Thompson, J. J., 1997. "Behavior and design of tension lap splices in reinforced concrete masonry", M. Eng. Thesis, Washington State University, Washington.

Experimental Program Design

❑ Test Matrix – Phase I: CMU

Specimen #	Bar Size	Factor	L_d Length (in)
1	**5**	**1**	**22**
2	**5**	**1.15**	**25**
3	5	1.3	28
4	7	1	56
5	**7**	**1.15**	**65**
6	**7**	**1.3**	**73**

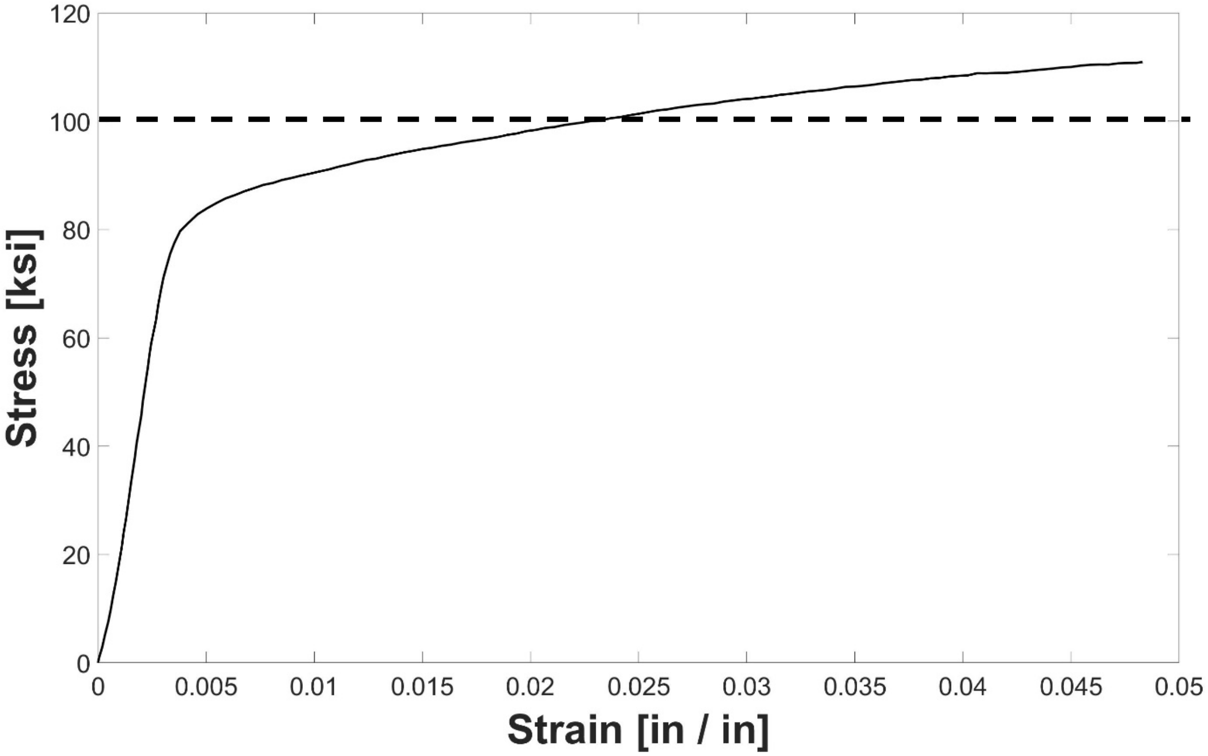
Phase II:
Additional CMU tests & Clay brick tests

Preliminary Test Results

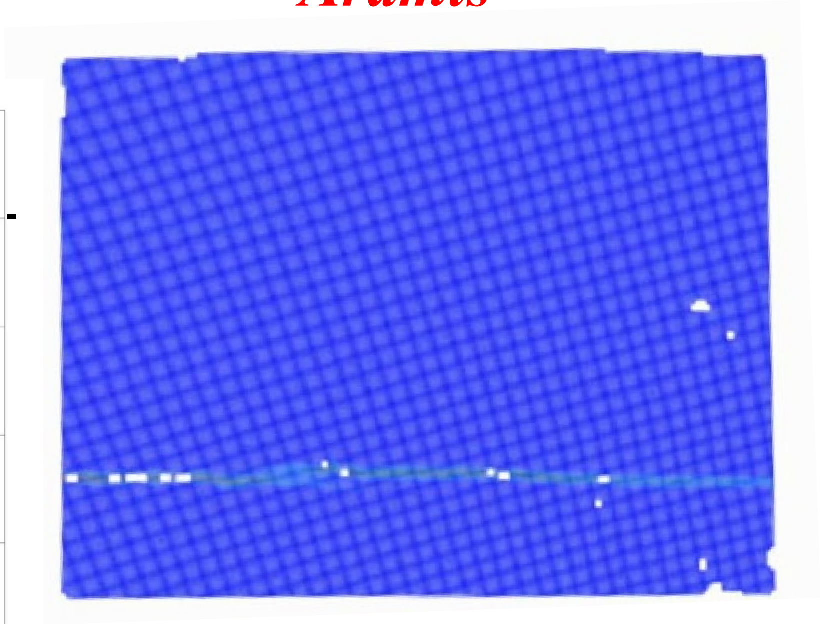
- Grade 80 #5 Reinforcing Bars

Video

Stress-Strain Response



Aramis



Material Tests

CMU

Grouted Prism

Grout

Reinforcing Steel

Un-grouted Prism

Mortar

References:

ASTM (C90-16a, C140, C109/C109M-99, C1019-16, C1314-16, A615/A615M-04a)

Summary of Test Results

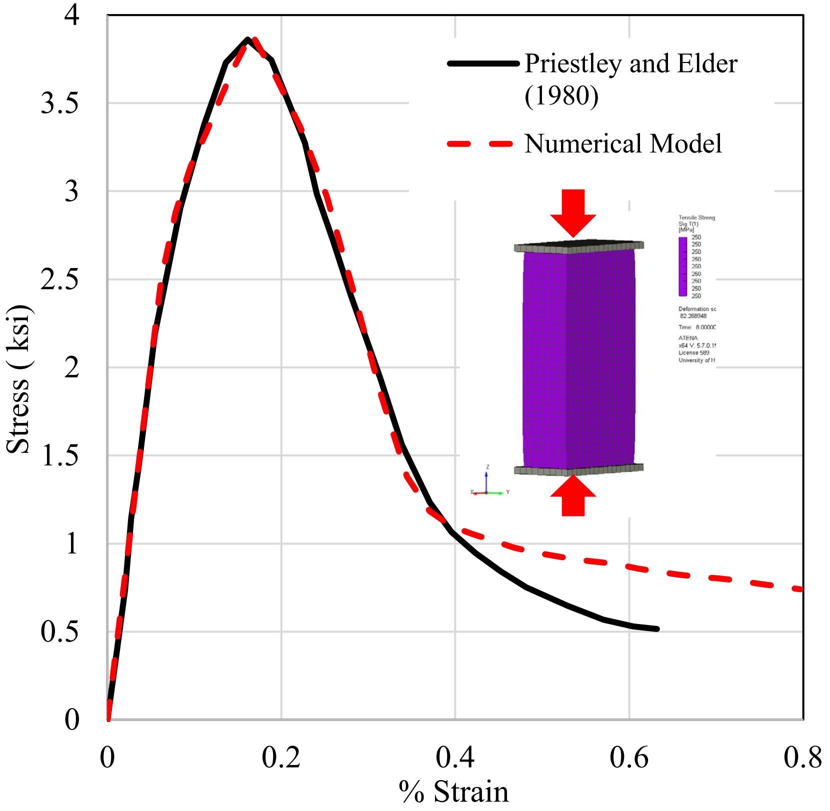
Specimen #	Reinforcement Grade	Splice Length	General mode of Failure	Failure Load (Stress)	corresponding f'm (ksi)	corresponding f'g (ksi)
1	**60**	# 5 @ 35 db 22 in	Longitudinal Split	25.8 kips 83.2 ksi	2.6	4.7
2	**80**	# 5 @ 35 db 22 in	Longitudinal Split	35.5 kips 114.6 ksi	3.0	3.4
3	**80**	# 5 @ 40 db 25 in	Coupler Failure	32.5 kips 104.8 ksi	3.0	3.4
4	**80**	# 5 @ 45 db 28 in			3.0	3.4
5	**80**	# 7 @ 64 db 56 in			3.0	3.4
6	**80**	# 7 @ 75 db 65 in	Longitudinal Split	63.8 kips 106.3 ksi	3.0	3.4
7	**80**	# 7 @ 84 db 73 in	Longitudinal Split	59 kips 98.3 ksi	3.0	3.4

Numerical Simulations

❑ Material Models

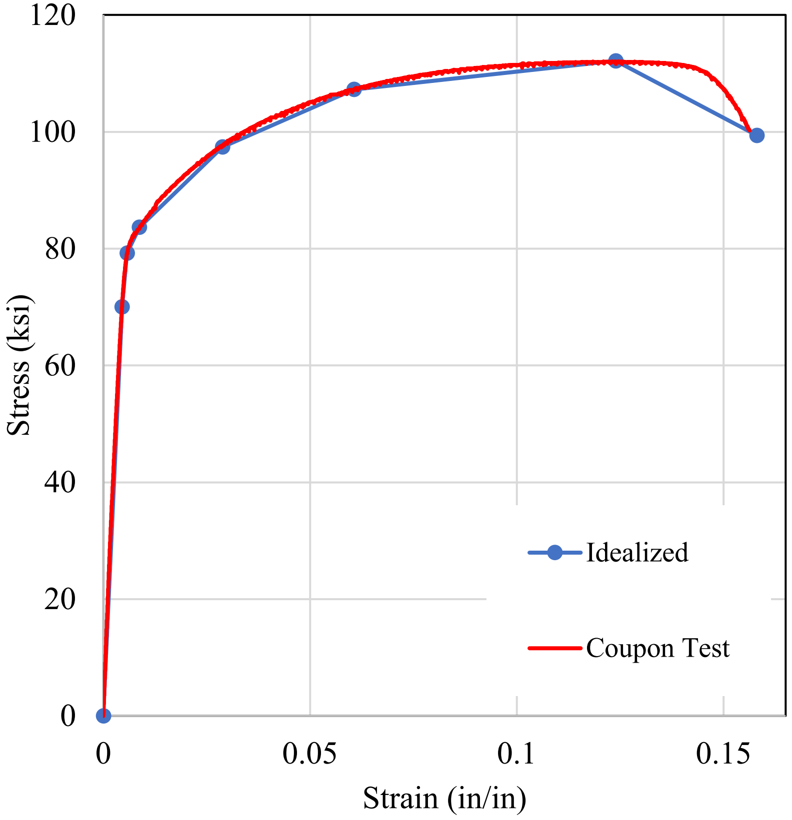
Masonry

Compressive Stress Strain Relation



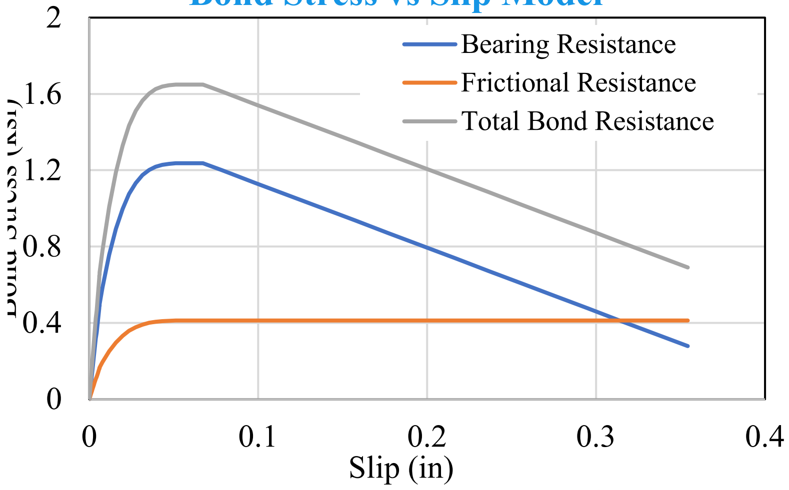
Reinforcing Steel

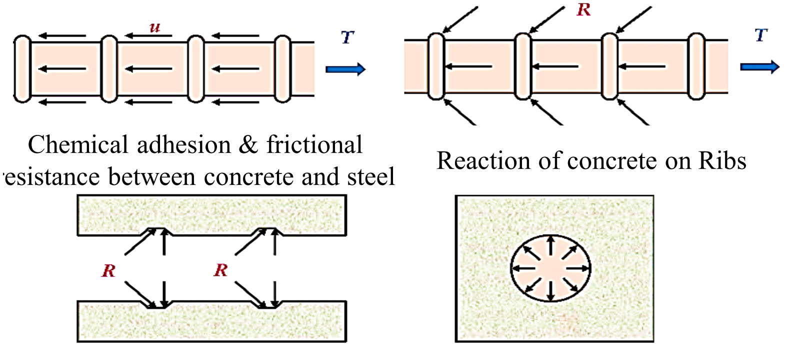
Grade 80 - Stress Strain Relation



Bond-Slip

Bond Stress vs Slip Model





Forces exerted by ribs on concrete

References:

1) Priestley, M.J.N and Elder, D.M , 1980. "Stress-Strain Curves for Unconfined and Confined Concrete Masonry," *ACI Journal*, Title No.80-19
2) Murcia-Delso, J and Shing, P.B, 2015. "Bond-Slip Model for Detailed Finite-Element Analysis of Reinforced Concrete Structures," *J. Struct. Eng.*, 141(4): 04014125
3) Tang C.W. and Cheng C.K., 2020. "Modeling Local Bond Stress–Slip Relationships of Reinforcing Bars Embedded in Concrete with Different Strengths," *Construction and Building Materials*, *13*(17), 3701

Numerical Simulations

- Verification with past tests

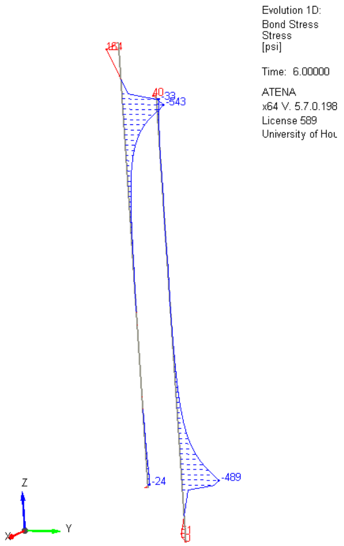
Specimen	Failure Load	Range of Experimental values from Thompson (1997)
#5@35db	31.53 kips (101.709 ksi)	26.4 – 31.2 kips
#5@48db	31.25 kips (100.806 ksi)	31.2- 32.4 kips
#7@35db	43.82 kips (72.911 ksi)	39.6 – 42 kips

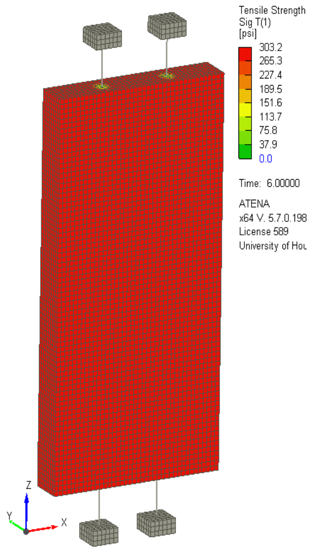
Reference:
Thompson, J. J., 1997. "Behavior and design of tension lap splices in reinforced concrete masonry", M. Eng. Thesis, Washington State University, Washington.

Numerical Simulations

- Comparisons with Grade 80 bar tests

Specimen	Panel Dimension (in)	Rebar	Splice Length (in)	Failure Load Predicted (kips)	Experimental Failure Load (kips)
1	31.625x39.625x7.625	#5	22	33.5	35.5
2	31.625x39.625x7.626	#5	25	31.9	32.5
3	31.625x39.625x7.627	#5	28		
4	63.625x39.625x7.629	#7	56		
5	71.625x39.625x7.630	#7	65	67.3	63.8
6	79.625x39.625x7.631	#7	73	67.4	59





Usage of Grade 80 Steel – Case Studies

❑ Case Studies

- **Design of a seven-story masonry load-bearing wall.**
- **Design of ten one-story in-plane reinforced masonry walls.**
- **Design a reinforced masonry pilaster.**
- **Design of Lintel.**
- **Design of four-story reinforced shear wall.**
- **Out of Plane wall.**

Summary and Ongoing Work

- Experimental work will continue to better understand the bond behavior of Grade 80 bars in masonry. **Selected tests** will be repeated. The effect of using **fiber-reinforced grout** will be studied with the intent to reduce the required development length.

- Verified numerical models will be used to study structural **masonry member** responses with Grade 80 bars.

- Case studies will identify **benefits in the use of Grade 80** bars and questions that need to be answered by **additional experimental studies**.

Acknowledgements

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