Raising Code Limits on Specified Reinforcement Strength By Adoption of High-Strength Steel Bars (HSRBs) In Structural Design

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THE MASONRY SOCIETY

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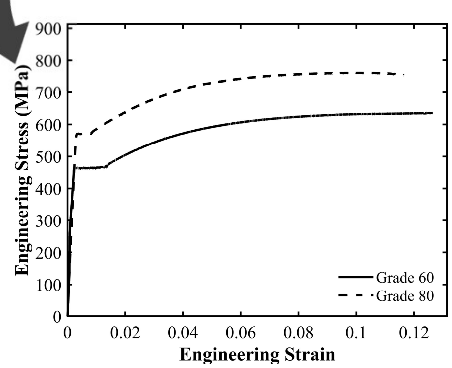
Why is the adoption important?

HSRBs: Bars with a specified yield strength greater than or equal to 80,000 psi (550 MPa). Most Relevant ASTM Standards: **A615, A706, A1035**



Why is adoption important?

- The general high-strength steel market was measured at **44.2 billion USD** in 2024, which marked a 50% increase from 2019 (29.6 billion USD)
- Significant **increase of HSRB production** by steel bar manufacturers driven by the RC industry
- **Reduce carbon footprint** in masonry buildings by lower steel ratios; gain member strength

https://www.marketsandmarkets.com/Market-Reports/high-strength-steel-market-4627428.html

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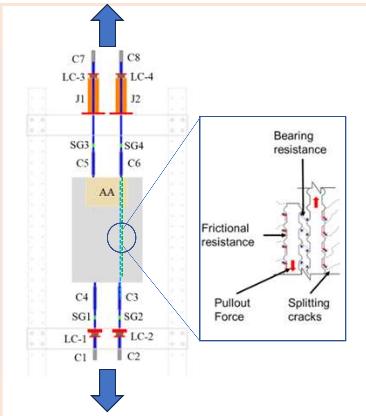
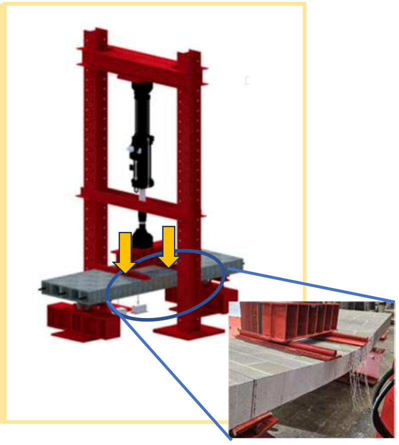
Experimental Program

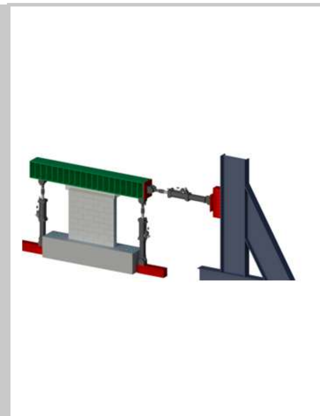
Lap-splice Length



Flexural Behavior



Shear Behavior



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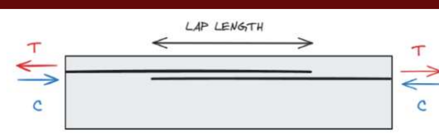
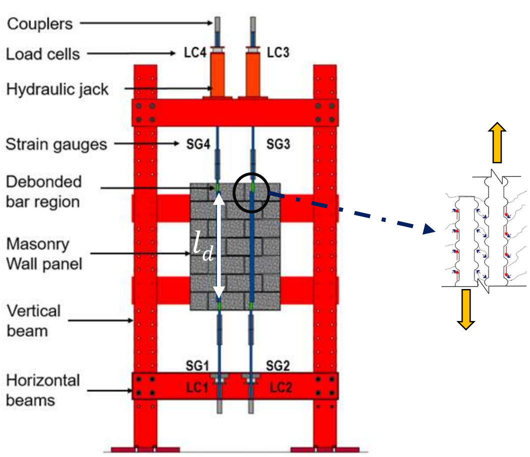
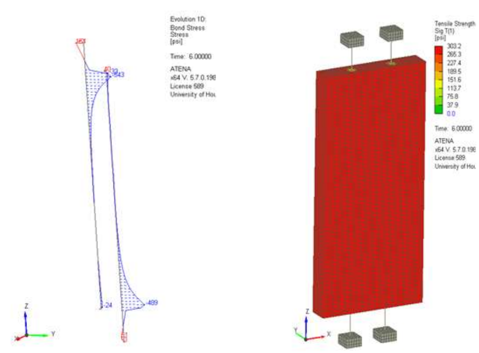
Lap-splice Length







Khalid, O., Khan, W., and Kallionzis, D. (2025). "Evaluating Lap-Splice Length Requirements for Grade 80 Deformed Bars in Structural Masonry." ASCE Journal of Structural Engineering, DOI: 10.1061/JSENDH/STENG-13571.

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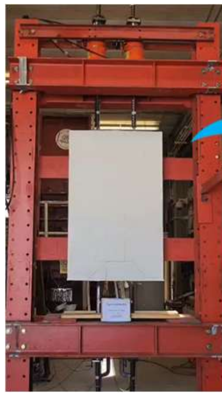
Lap-splice Length

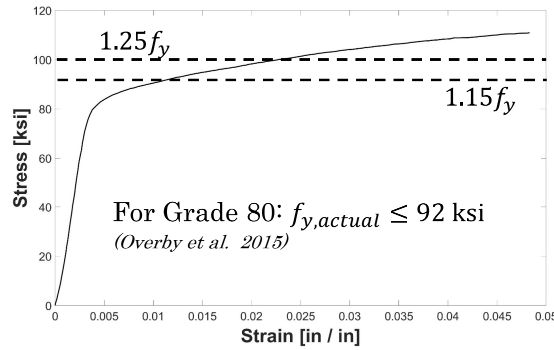
Lap-Splice Test with No. 5 Grade 80 bars

Lap-Splice Test with No. 7 Grade 80 bars



TMS 402-22

$$l_d = \frac{0.13 d_b^2 f_y \gamma}{K\sqrt{f'_m}} \rightarrow 1.25 f_y$$



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Lap-splice Length

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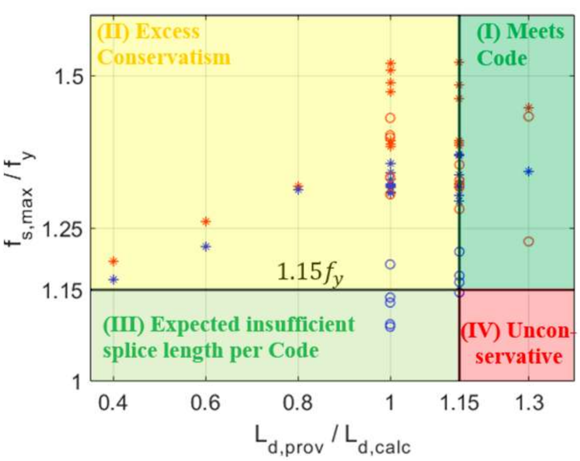
Development Length Requirements for Grade 80 bars



$$l_d = \frac{0.13 d_b^2 f_y \Psi_s \Psi_g}{K\sqrt{f'_m}} \geq 12.0 \text{ in}$$

- A rebar grade factor $\Psi_g = 1.15$ proposed for Grade 80 bars. The factor is $\Psi_g = 1.0$ for Grade 40 or 60 bars.
- A706 bars performed more reliably and had lower lap-splice length requirements. All tested Grade 80 A706 bars achieved the 125% f_y criterion for $\boldsymbol{\Psi_g = 1.00}$.
- A615 failed the 125% f_y criterion set by TMS 402 for $\Psi_g = 1.00$ and $\boldsymbol{\Psi_g = 1.15}$.
- Equation 6-2: overly conservative for smaller bar sizes and less conservative or liberal for larger bar sizes.
- *The requirement of an added safety factor of 125% f_y is excessive for non-seismic applications where A615 are mostly used.*

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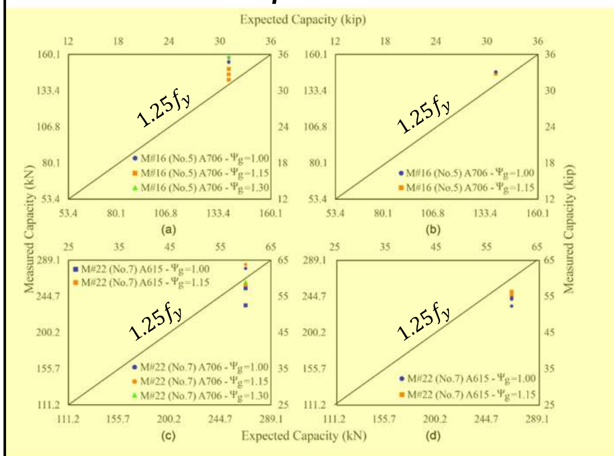
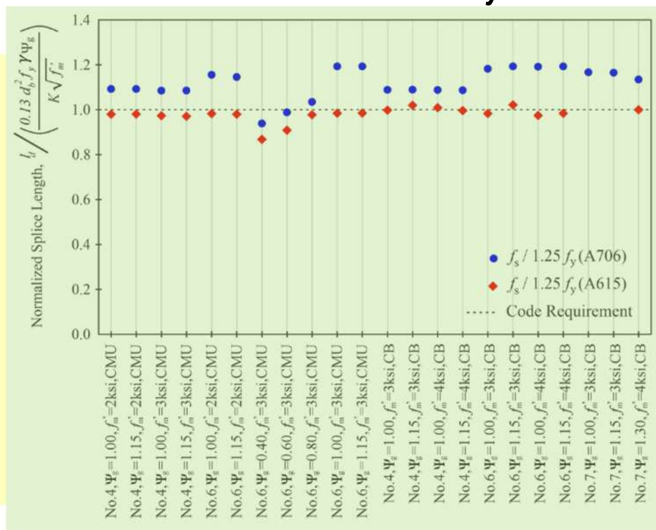
Lap-splice Length

Some Experimental Data



Parametric Finite Element Analysis



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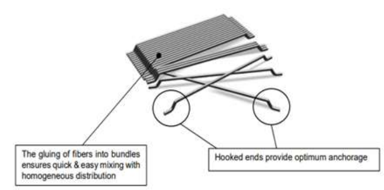
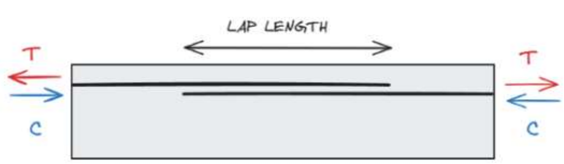
Can we do better?

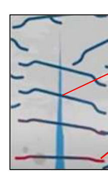
$$l_d = \frac{0.13 d_b^2 f_y \Psi_s \Psi_g}{K\sqrt{f'_m}} \geq 12.0 \text{ in}$$

$\times$ ***Ψ_{fg}= Fiber-reinforced Grout Factor***

Bar size Imperial (Metric)	Grade 60 bar l_d, in. (mm)	Grade 80 bar l_d, in. (mm)	$l_{d,80} / l_{d,60}$
No. 3 (Φ 10)	12 (305) or $32d_b$	14 (356) or $73.3d_b$	1.17
No. 4 (Φ 12)	12 (305) or $24d_b$	15.5 (394) or $31d_b$	1.29
No. 5 (Φ 16)	16 (406) or $25.6d_b$	24.5 (622) or $39.2d_b$	1.53
No. 6 (Φ 20)	30.5 (775) or $40.7d_b$	46.5 (1,181) or $62d_b$	1.53
No. 7 (Φ 22)	42 (1,067) or $48d_b$	64.5 (1,638) or $73.7d_b$	1.53
No. 8 (Φ 25)	64 (1,626) or $64d_b$	99 (2,515) or $99d_b$	1.53
No. 9 (Φ 29)	83 (2,108) or $73.6d_b$	128.5 (3,264) or $113.9d_b$	1.53







Crack Control

Anchorage

Diameter of Fiber= 0.55 mm

DRAMIX 3D 55/30

Length of Fiber= 30 mm

Nominal Tensile Capacity of 1345 MPa (195 ksi)

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Lap-splice Tests with Fiber-Reinforced Grout

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Lap-splice Tests with Fiber-Reinforced Grout

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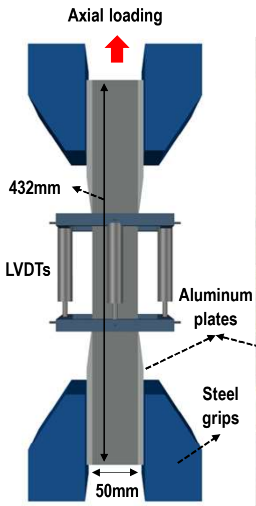

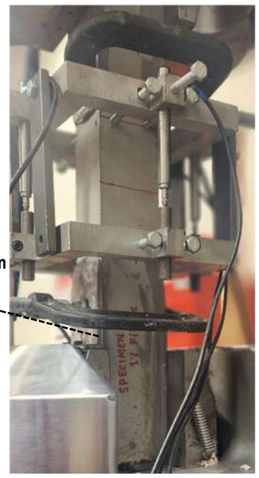

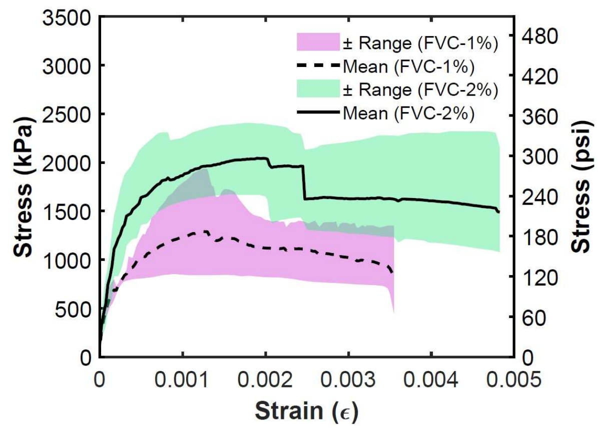

Direct Tension Tests

1% Fibers by volume → 187 psi

2% Fibers by volume → 296 psi

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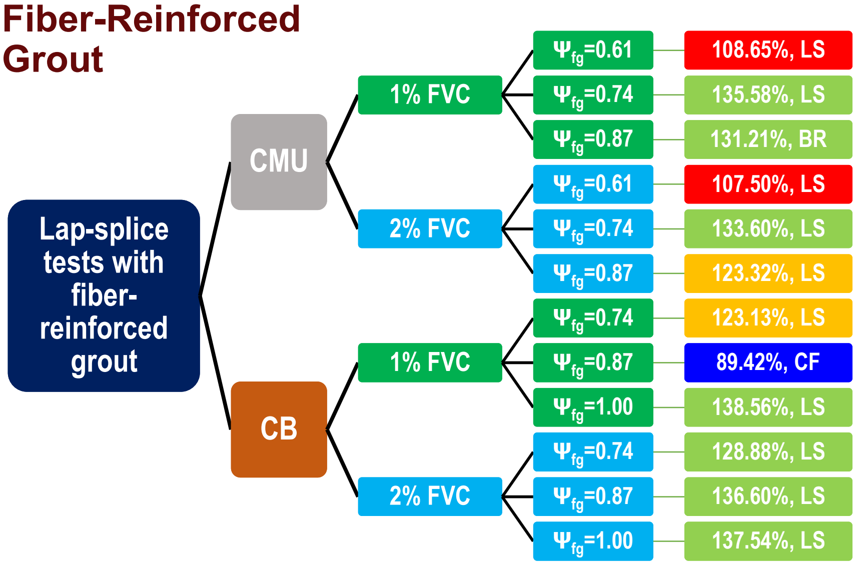
Lap-splice Tests with Fiber-Reinforced Grout



LS= Longitudinal Splitting
BR= Bar Rupture
CF= Coupler failure

Smaller
Greater
Approx.equal
Not applicable

Ψ_{fg}=0.74

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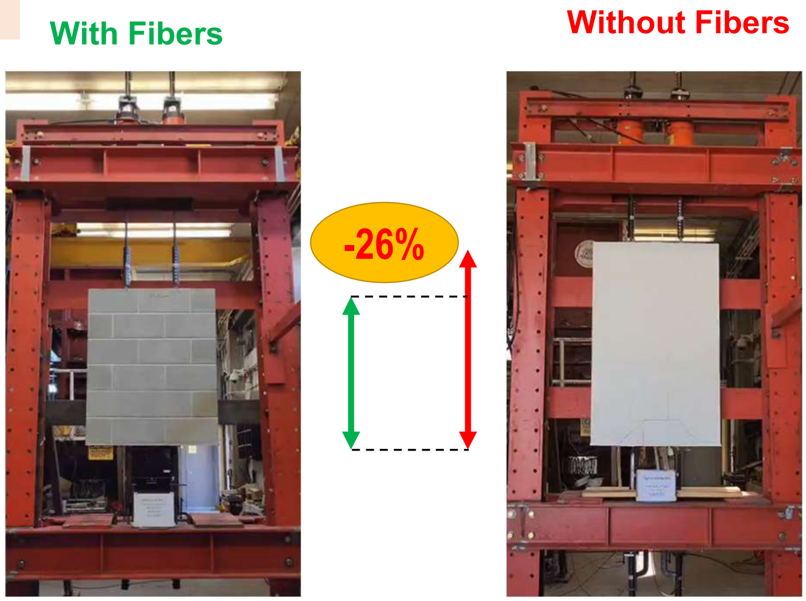
Conclusion

$\Psi_{fg} = 0.74$

Decrease in required development length by 26%

Improved Integrity



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Flexural Behavior

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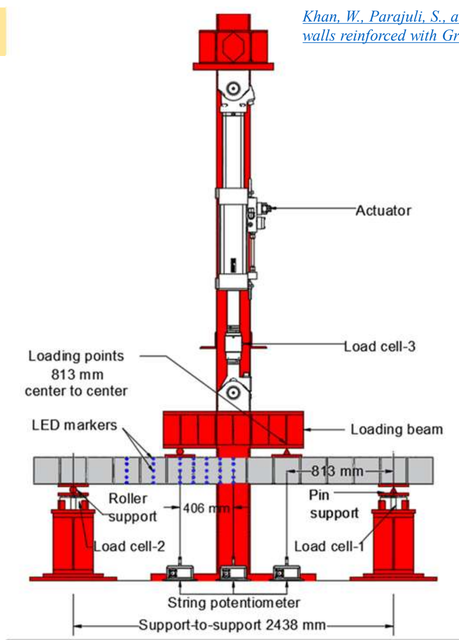

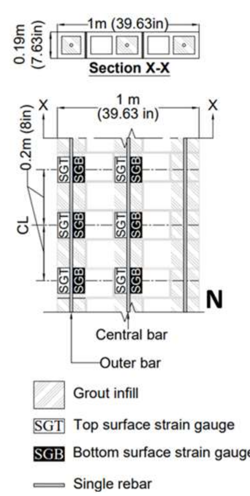

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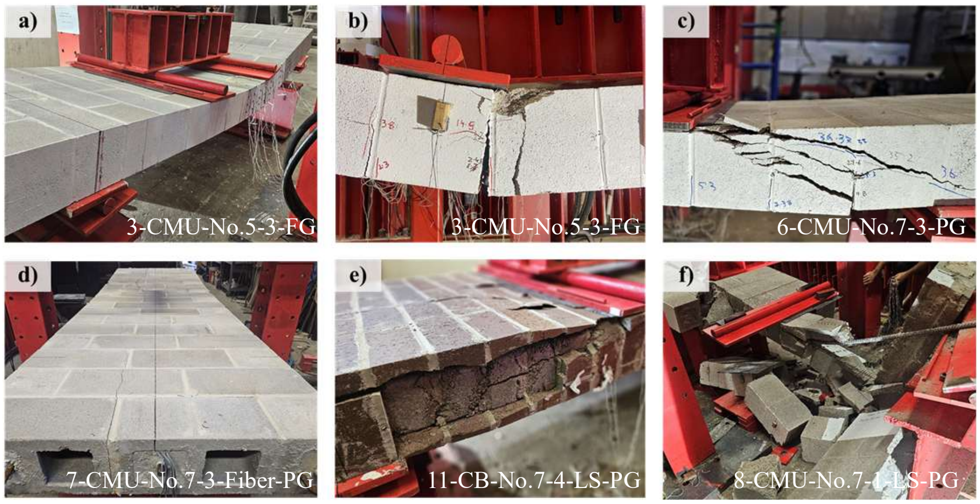
Highlights



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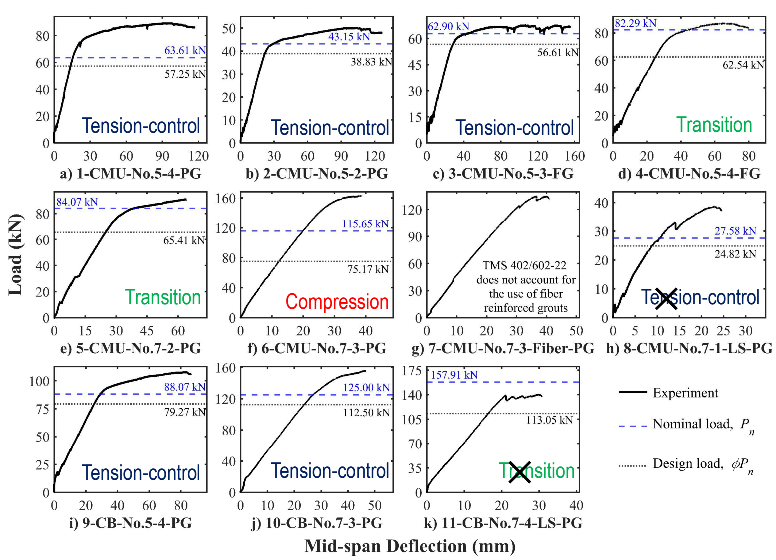
Load-Deflection Curves



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Evaluation with TMS 402-22: Strength Design

Wall name	P_{ult}, kN (kips)	$\epsilon_{s,ult}$	Δ_{peak}, mm (in)	Δ_y, mm (in)	Δ_{ult}, mm (in)	$\mu = \Delta_{ult}/\Delta_y$	$P_{ult}/(\phi P_n)$
1-CMU-No.5-4-PG	89.4 (20.1)	0.0332	98 (3.8)	16 (0.6)	119 (4.7)	7.44	1.56
2-CMU-No.5-2-PG	50.7 (11.4)	0.0259	104 (4.1)	22 (0.9)	129 (5.1)	5.86	1.29
3-CMU-No.5-3-FG	67.6 (15.2)	0.0277	107 (4.2)	26 (1.0)	155 (6.1)	5.96	1.20
4-CMU-No.5-4-FG	87.2 (19.6)	0.0162	65 (2.6)	26 (1.0)	83 (3.3)	3.19	1.39
5-CMU-No.7-2-PG	91.6 (20.6)	0.0152	69 (2.7)	26 (1.0)	79 (3.1)	3.04	1.40
6-CMU-No.7-3-PG	163.2 (36.7)	0.0086	39 (1.5)	23 (0.9)	42 (1.7)	1.83	2.17
7-CMU-No.7-3-Fiber-PG	134.8 (30.3)	0.0050	37 (1.4)	29 (1.2)	42 (1.7)	1.45	n.a.
8-CMU-No.7-1-LS-PG	38.7 (8.7)	0.0020	23 (0.9)	n.m.	31 (1.2)	n.m.	1.56
9-CB-No.5-4-PG	107.6 (24.2)	0.0190	84 (3.3)	25 (1.0)	93 (3.6)	3.72	1.36
10-CB-No.7-3-PG	156.1 (35.1)	0.0102	47 (1.9)	26 (1.0)	48 (1.9)	1.85	1.39
11-CB-No.7-4-LS-PG	140.1 (31.5)	0.0017	30 (1.2)	n.m.	31 (1.2)	n.m.	1.24

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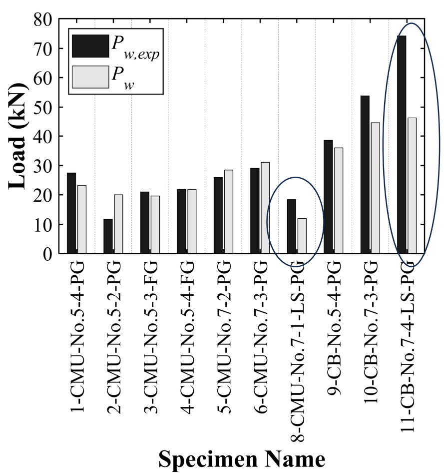
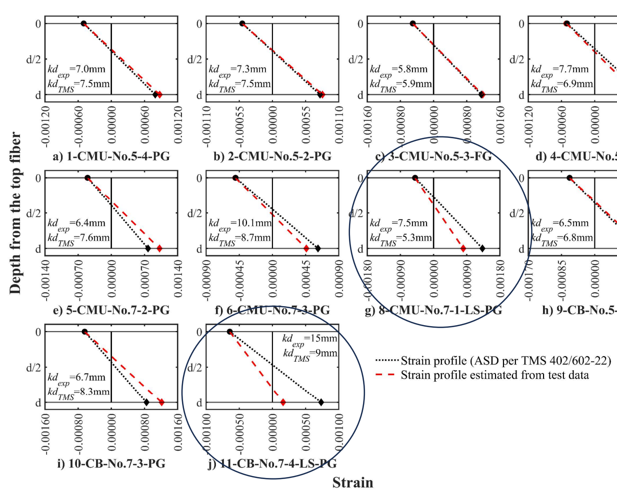
Evaluation with TMS 402-22: Allowable Stress Design





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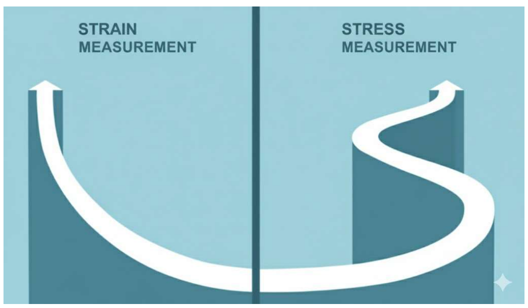
ASD limit state definition

Allowable stresses (per TMS 402-22) :

- Masonry: $F_m = 0.45f'_m$
- Steel: $F_t = 32$ or 42 ksi → Grade 60 or Grade 80



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Corresponding allowable strain:

Hooke's Law

Masonry: $\varepsilon_{m,allow} = F_m/E_m$

Steel: $\varepsilon_{s,allow} = F_t/E_s$

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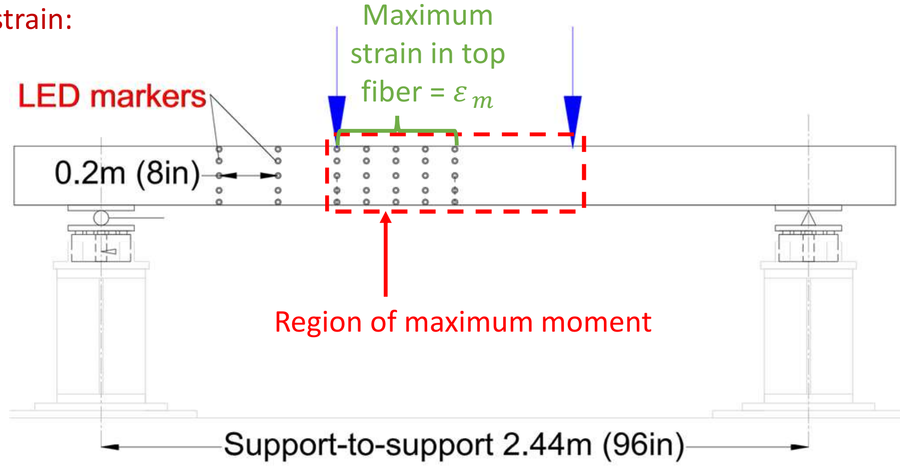
Measuring the strains

Steel strain: Strain gauges

Masonry strain:



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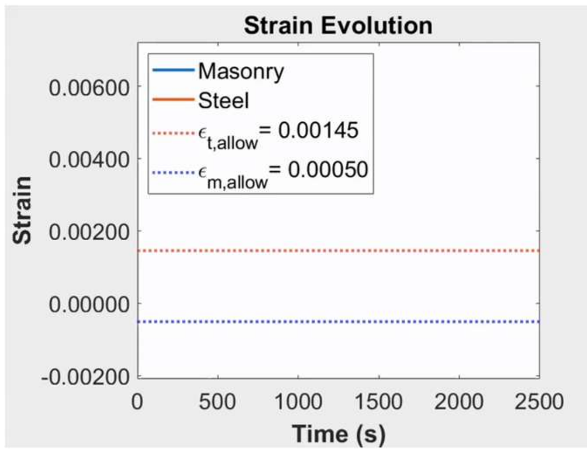
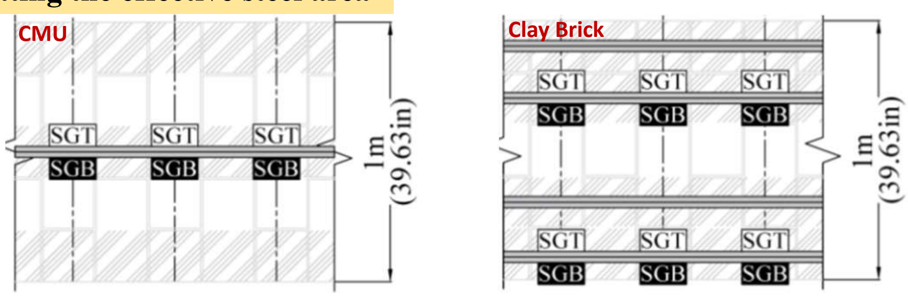
ASD limit state

- Masonry and steel strains are continuously monitored.



The first material to reach its allowable strain governs ASD.

Back-calculating the effective steel area



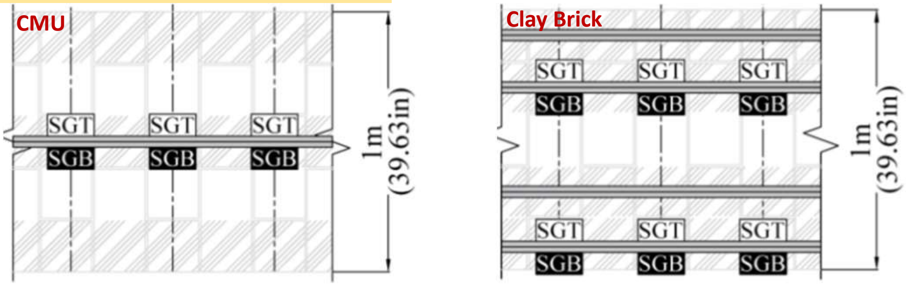
8-CMU-No.7-1-LS-PG

11-CB-No.7-4-LS-PG

LAP SPLICED NUMBER 7 BARS

	Wall 8	Wall 11
Area of steel considered	0.6 in^2	[0.6 x 4] = 2.4 in^2
Load at ASD limit state	4.16 kips	17.64 kips
Corresponding moment	66.62 kip-in	282.26 kip-in
Neutral axis depth (kd) determined from masonry and steel strains.		
Area of steel contributing	**0.86 in^2**	**4.57 in^2**

Back-calculating the effective steel area



8-CMU-No.7-1-LS-PG

11-CB-No.7-4-LS-PG

LAP SPLICED NUMBER 7 BARS

	Wall 8	Wall 11
Area of steel considered	**0.6 in^2**	[0.6 x 4] = **2.4 in^2**
Load at ASD limit state	[illegible] kips	[illegible] kips
Neutral axis depth (kd) determined from masonry and steel strains.		
Area of steel contributing	**0.86 in^2**	**4.57 in^2**

+43 % increase

+90 % increase

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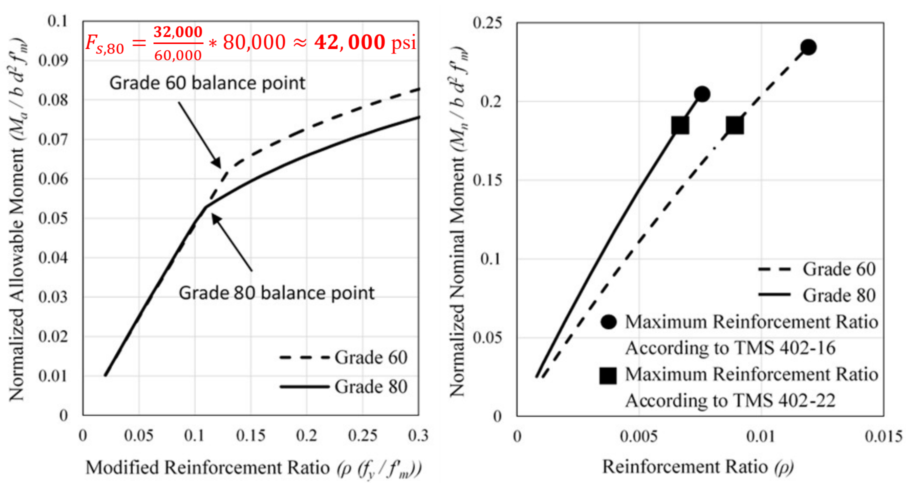
TMS 402/602 & Grade 80 Bars



(a) ASD

(b) SD

Khalid, O., and Kallionztis, D. (2023). "High-strength reinforcing bars (HSRBs) and TMS 402: A first study on Grade 80 bars." TMS Journal, December 2023.

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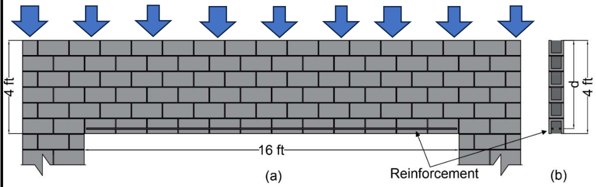
TMS 402/602 & Grade 80 Bars



Parameter definition	Loading scenario A	Loading scenario B
Dead load, D_L	700 lb./ft	2,000 lb./ft
Live load, L_L	300 lb./ft	700 lb./ft
Masonry unit	8-in. medium weight CMU	
Lintel beam clear span	16 ft	
Lintel beam depth	4 ft	
Steel modulus, E_s	29,000,000 psi	
Masonry compressive strength, f'_m	2,000 psi	

MDG (2016)

Allowable Stress Design				
	Grade 60		Grade 80	
Required area of tension steel (in^2)	Scenario A 0.402	Scenario B 1.09	Scenario A 0.304	Scenario B 0.820
$A_{s,required,80}/A_{s,required,60}$	0.75	0.75	-	-
Strength Design				
	Grade 60		Grade 80	
Required area of tension steel (in^2)	Scenario A 0.294	Scenario B 0.794	Scenario A 0.221	Scenario B 0.595
$A_{s,required,80}/A_{s,required,60}$	0.75	0.75	-	-

Table Notes: (1) $A_{s,required,80}$ = required area of tension steel with Grade 80 bars; (2) $A_{s,required,60}$ = required area of tension steel with Grade 60 bars.

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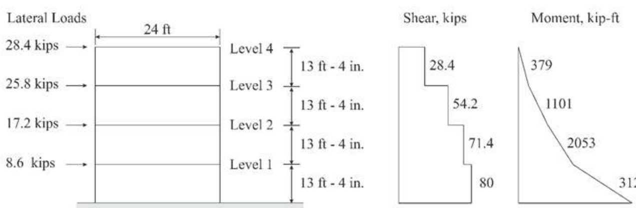
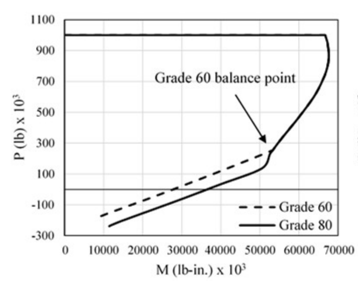
TMS 402/602 & Grade 80 Bars

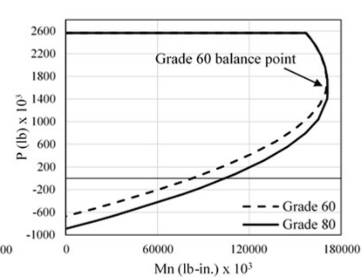


Wall length, L	24 ft
Steel modulus, E_s	29,000,000 psi
Masonry unit	8-in. CMU
Masonry compressive strength, f'_m	2,500 psi
Flexural reinforcement, ASD and Grade 60 bars	No. 5 @ 8 in. ($\rho = 0.0051$)
Flexural reinforcement, ASD and Grade 80 bars	No. 4 @ 8 in. ($\rho = 0.0033$)
ρ_{max} per ASD (Equation 8-20 in TMS 402-16 and Equation 8-18 in TMS 402-22)	0.0073 for Grade 60 and 0.0045 for Grade 80 bars
ρ_{max} per SD (Section 9.3.3.2 in TMS 402-16/22)	0.0034 for Grade 60 and 0.0016 for Grade 80 bars
A_s/d_v (Section 9.3.3.2 in TMS 402-16 and Section 9.3.5.6.1 in TMS 402-22), in^2/ft	0.049 for Grade 60 and 0.02 for Grade 80 bars

MDG (2016)



(a) ASD



(b) SD

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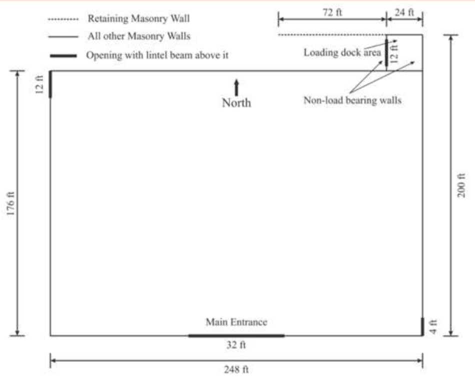
TMS 402/602 & Grade 80 Bars



Bar #	Bar weight lb./ft	Number of feet per ton	Grade 60 price per foot, $	Grade 60 price per ton, $	Grade 80 price per ton, $	Grade 60 price per foot, $
3	0.376	5,319.1	0.70	3,723.4	3,873.4	0.73
4	0.668	2,994.0	0.90	2,694.6	2,844.6	0.95
5	1.043	1,917.5	1.40	2,684.5	2,834.5	1.48
6	1.502	1,331.6	2.29	3,049.4	3,199.4	2.40
7	2.044	978.5	3.33	3,258.4	3,408.4	3.48
8	2.67	749.1	4.08	3,056.3	3,206.3	4.28

Masonry member	Bar size	Grade 60 No. 5 bars		Bar size	Grade 80 No. 4 bars	
		Required length ft	Price $		Required lengths	Price $
Out-of-Plane, load bearing	No. 5	20,095	28,133	No. 4	20,047	19,044.65
Out-of-Plane, non-load bearing	No. 5	736	1,030.4	No. 4	733	696.35
Lintel above entrance	No. 5	1,690	2,366	No. 4	1,688	1,603.6
Other lintel beams	No. 5	28	39.2	No. 4	28	26.6
Shear wall	No. 5	4,582	6,414.8	No. 5	4,859	7,191.32
Retaining wall	No. 5	336	470.4	No. 4	252	239.4
Total rebar cost		$38,453.8			$28,801.92	

cost reduction for reinforcing bar material was 25%

Khalid, O., and Kalliontzis, D. (2023). "High-strength reinforcing bars (HSRBs) and TMS 402: A first study on Grade 80 bars." TMS Journal, December 2023.

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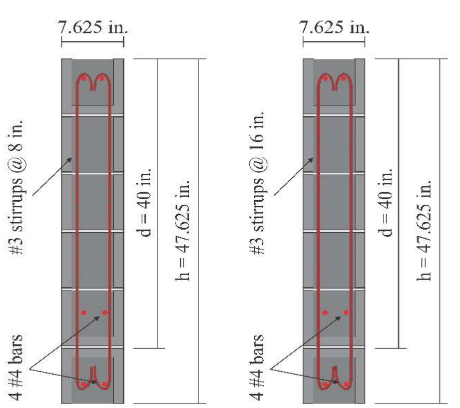
TMS 402/602 & Grade 80 Bars

Grade 60 – SD

Grade 80 – SD



This lintel design case highlights that lightly reinforced members may <u>not</u> always benefit from Grade 80 bars if the absolute difference between the required reinforcement areas is small, and the designer has to follow a specific construction scheme

Khalid, O., and Kalliontzis, D. (2023). "High-strength reinforcing bars (HSRBs) and TMS 402: A first study on Grade 80 bars." TMS Journal, December 2023.

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Summary

- Greater benefits result from the design of Grade 80-reinforced masonry members with the **SD than the ASD** procedure.
- Significant **savings in cost**. Reduced carbon footprint. Gain in strength.
- $\boldsymbol{\Psi_g = 1.15}$ for Grade 80 bars in lap length design.
- Adequate conservatism and robustness for both the ASD and SD procedures in **flexural design**.
- Lap-spliced bars: A larger bar area (>1.4 x A_s) contributes to the ASD state.
- Lower lap lengths for A706 versus A615 bars. We could use $\boldsymbol{\Psi_g = 1.00}$ **for A706.**
- Do **not** use lap-splices in plastic hinge regions that require high ductility (seismic zones)

Khalid, O., and Kalliontzis, D. (2023). "High-strength reinforcing bars (HSRBs) and TMS 402: A first study on Grade 80 bars." TMS Journal, December 2023.

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