Assessment of the Lap Splice Length Equation for GFRP Rebars in tension

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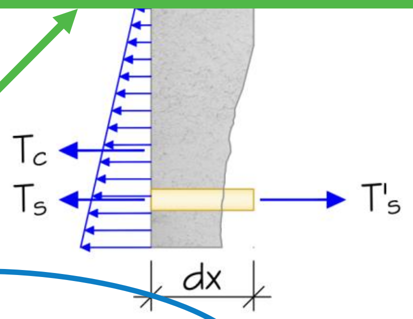
ACI 440.11 / Wambeke and Shield (2006)

$$\mu_{AvgW\&S} = \left[4.0 + 0.3\frac{c_b}{d_b} + 100\frac{d_b}{l_{embed}}\right]\kappa\sqrt{f'_c}$$

Length of embedded reinforcement required to develop the required bar stress.

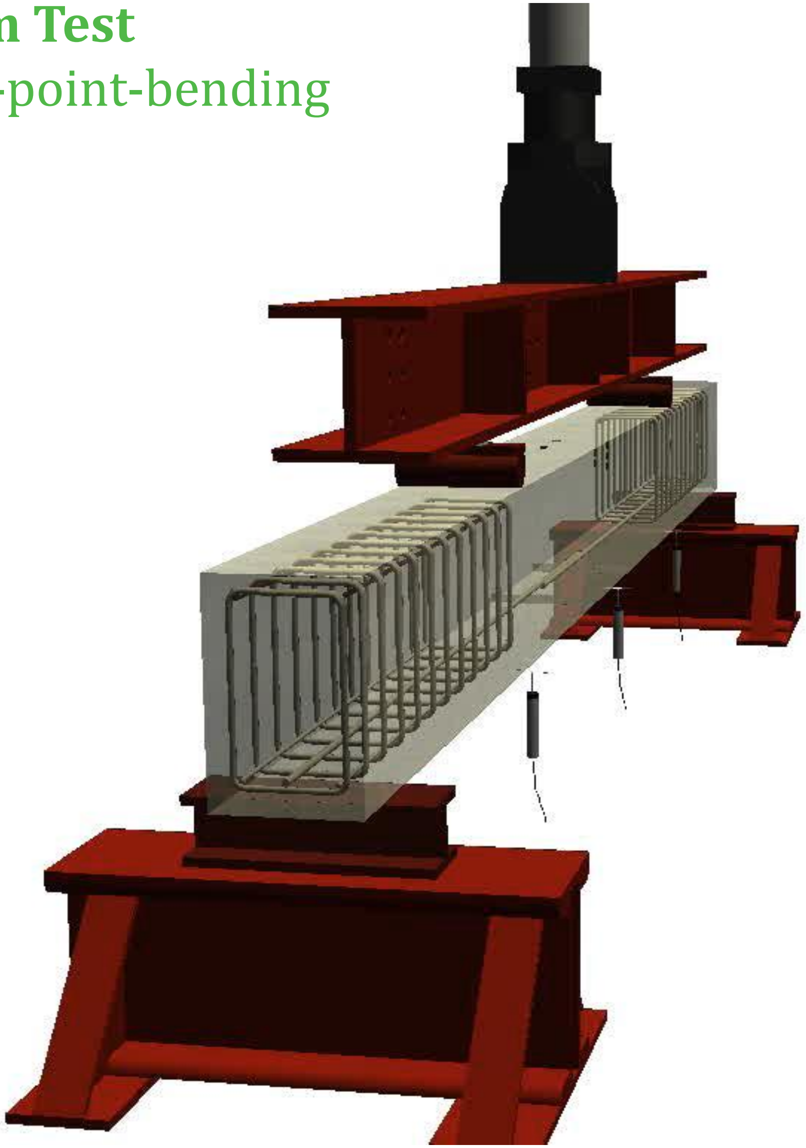
$$l_d = \frac{\left(\frac{f_{fr}}{\kappa\sqrt{f'_c}} - 340\right)\Psi_t}{13.6 + \frac{c_b}{d_b}} d_b$$



$$u = \frac{f_f\, d_b}{4\, l_{embed}}$$

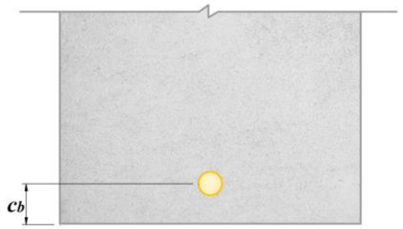
- Existing development length equations might yield **large values** of embedment length, leading to challenges in detailing, congestion of bars, and material usage.
- So far, **no unified model** is available that can be applied to the general bond behavior of GFRP bars. Some authors have proposed models and statistically-based expressions for it.
- Findings from the available literature present **conflicting perspectives** regarding the reliability of the current equation.

Beam Test
Four-point-bending



Parameters to be evaluated

Concrete cover



- ✓ 38 mm (1.5 in.)
- ✓ 19 mm (3/4 in.)

Lap Splice Length

- ✓ $40d_b$ (630 mm)
- ✓ $60d_b$ (950 mm)
- ✓ $80d_b$ (1270 mm)

Under-Reinforced Concrete Beam

M16 (No. 5) GFRP Sand-Coated Rebar

Single bar – No confining reinforcement

16 concrete beams – 2 repetitions each

Under-Reinforced Concrete Beam

M16 (No. 5) GFRP Sand-Coated Rebar

Single bar – No confining reinforcement

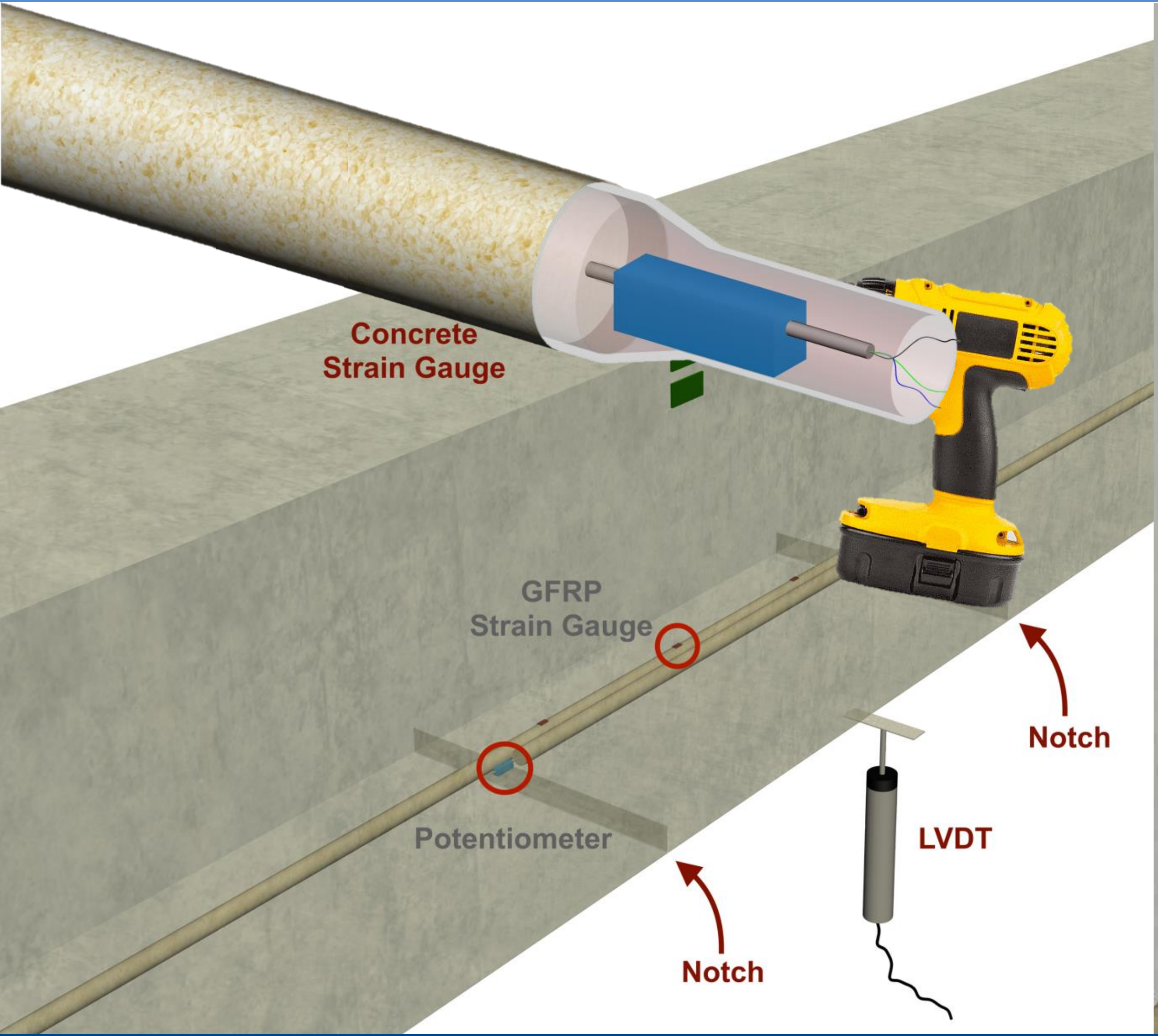
f'c
40 MPa
6000 psi

Characterization	Standard	Average (μ)	Std Dev (σ)
Fiber mass content	ASTM D2584	83%	0.2%
Glass transition temperature	ASTM E1356	113 °C (235 °F)	9.6 °C (17.2 °F)
Degree of cure	CSA S807	99%	0.3%
Measured cross-sectional area	ASTM D7205	238 mm^2 (0.369 $in.^2$)	3.5 mm^2 (0.0054 $in.^2$)
Ultimate tensile force	ASTM D7205	264 kN (59.3 kip)	6 kN (1.35 kip)
Ultimate tensile strength	ASTM D7205	1326 MPa (192 ksi)	30.1 MPa (4.4 ksi)
Tensile modulus of elasticity (E_f)	ASTM D7205	64.9 GPa (9416 ksi)	1.07 GPa (154 ksi)
Ultimate tensile strain	ASTM D7205	2.04%	0.06%
Ultimate transverse shear force	ASTM D7617	90 kN (20.2 kip)	1.2 kN (0.28 kip)
Ultimate transverse shear strength	ASTM D7617	226 MPa (33 ksi)	3.1 MPa (0.4 ksi)
Moisture absorption (24h)	ASTM D570	0.07%	0.003%
Bond strength	ASTM D7913	17.1 MPa (2.48 ksi)	1.7 MPa (0.25 ksi)

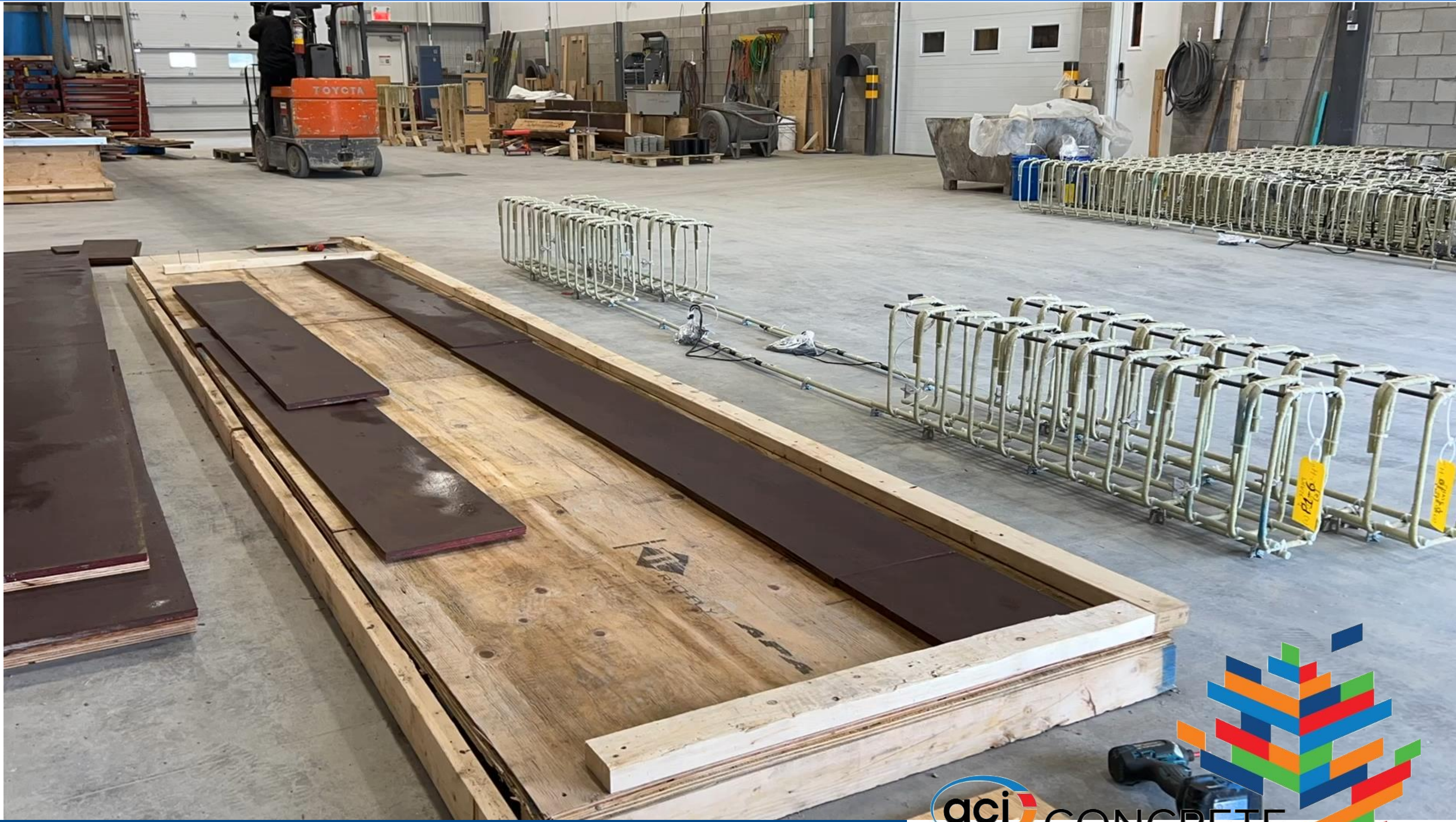
ASTM INTERNATIONAL

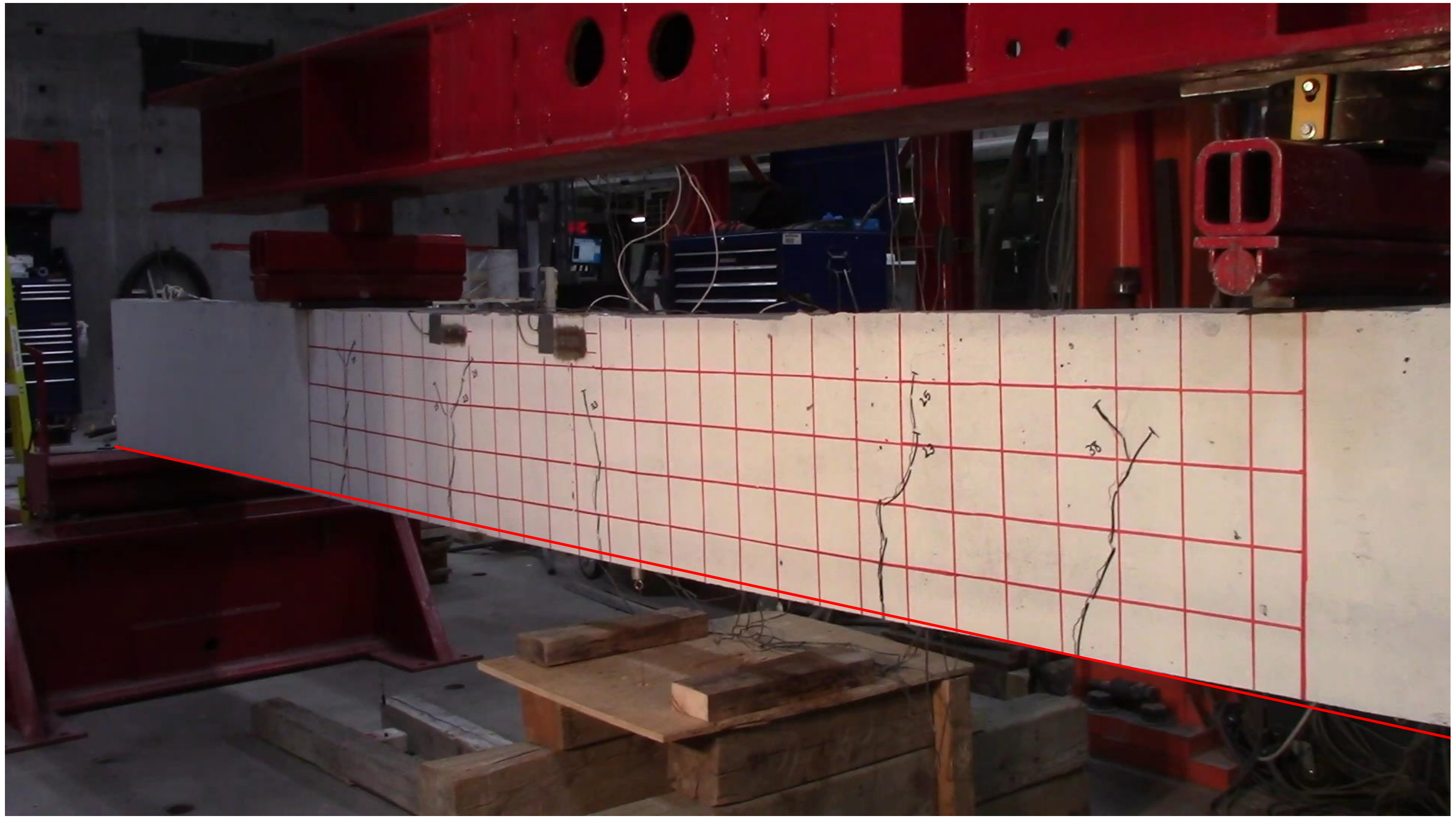
Glass + Vinyl ester FRP Rebar

Instrumentation

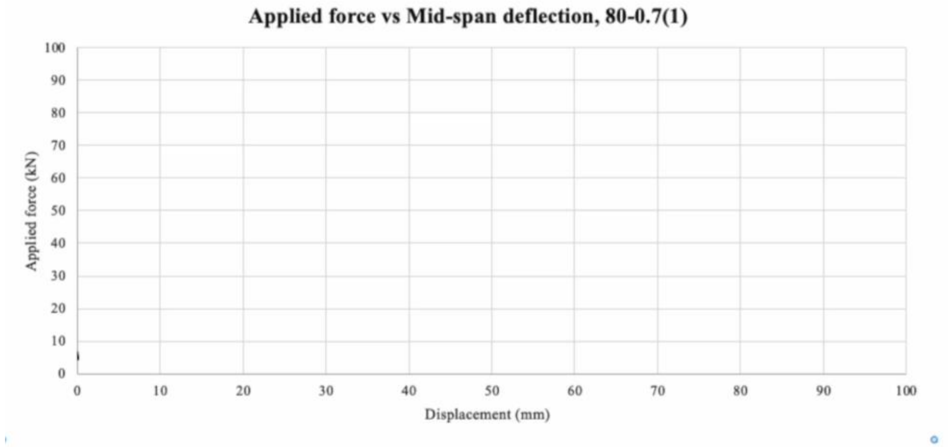


Fabrication process



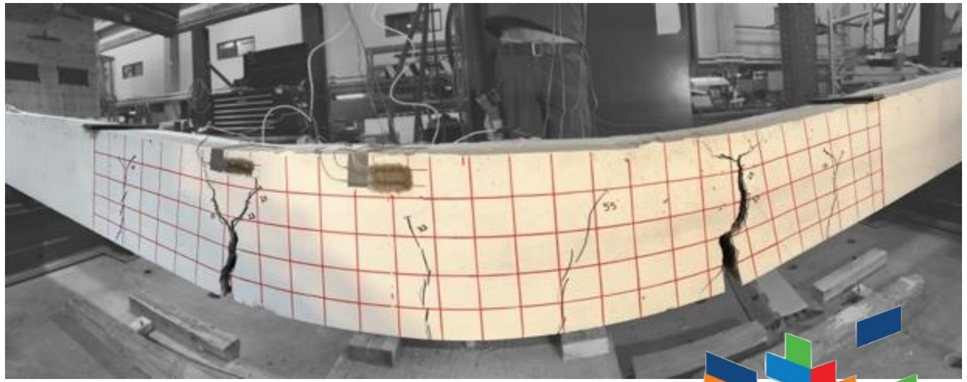


$80\ db\ lap\ splice, 19\ mm - cc$



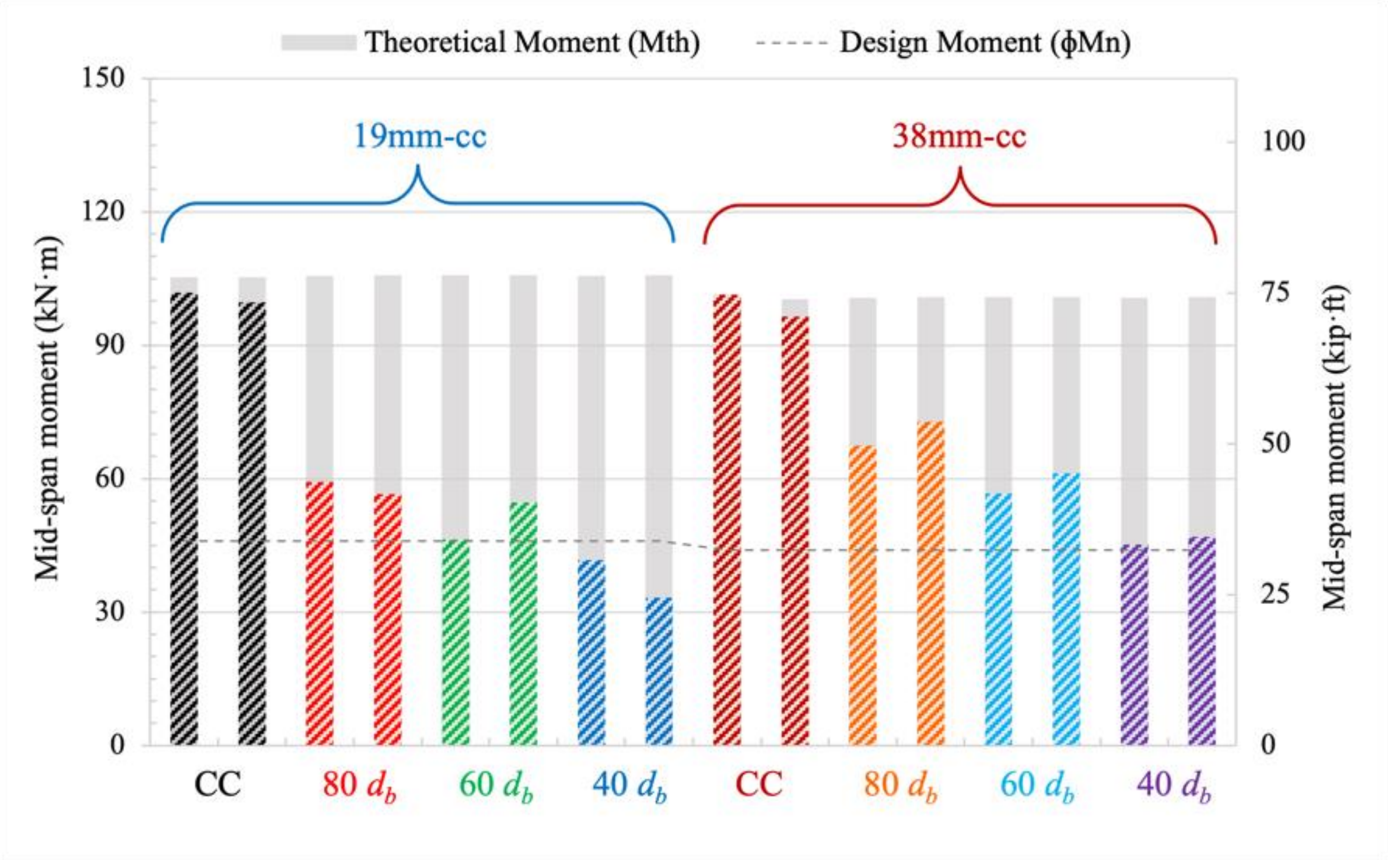
ID	Displm.	Force	Time
35	0.04 mm	7.80 kN	43 s

Displacement		Applied force	
Min	0 mm	Min	5 kN
Max	76.27 mm	Max	87.2 kN



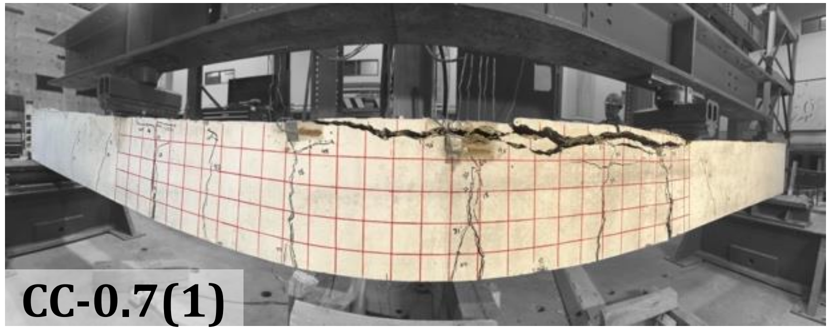
Splitting

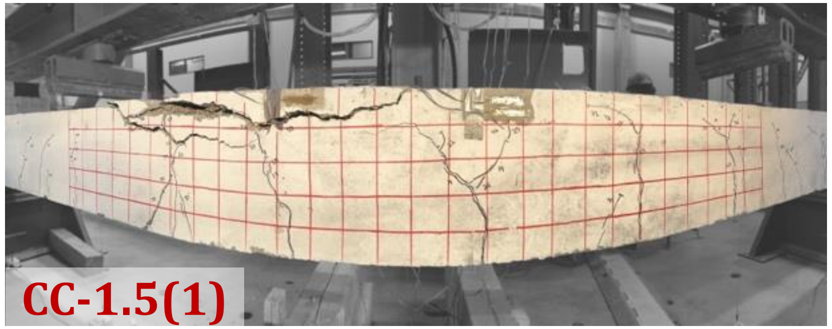
Results

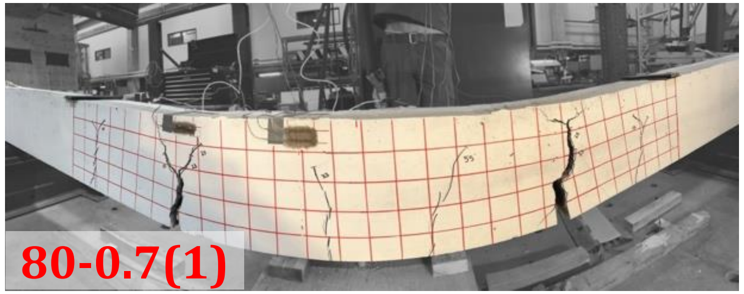


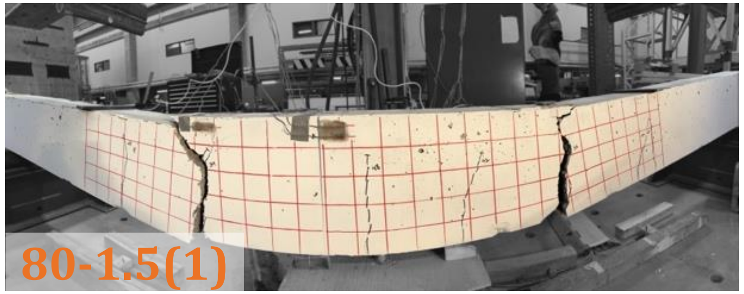
Specimen	Mid-span deflection (mm)	Mtest / Mth	Mtest / φMn	Failure mode
CC-0.7(1)	151	0.97	2.21	Concrete crushing
CC-0.7(2)	147	0.94	2.16	Concrete crushing
80-0.7(1)	76	0.56	1.29	Splitting
80-0.7(2)	55	0.53	1.23	Splitting
60-0.7(1)	48	0.44	1.01	Splitting
60-0.7(2)	64	0.52	1.19	Splitting
40-0.7(1)	40	0.39	0.90	Splitting
40-0.7(2)	26	0.31	0.72	Splitting
CC-1.5(1)	147	1.01	2.30	Concrete crushing
CC-1.5(2)	131	0.96	2.19	Concrete crushing
80-1.5(1)	66	0.67	1.53	Splitting
80-1.5(2)	78	0.72	1.65	Splitting
60-1.5(1)	65	0.56	1.29	Splitting
60-1.5(2)	72	0.61	1.39	Splitting
40-1.5(1)	40	0.45	1.03	Splitting
40-1.5(2)	46	0.46	1.06	Splitting

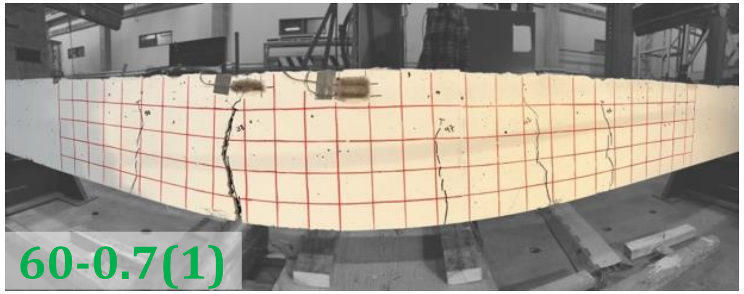
Structural Behavior

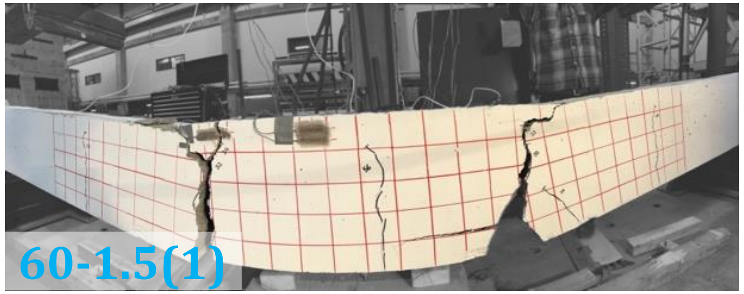

CC-0.7(1)

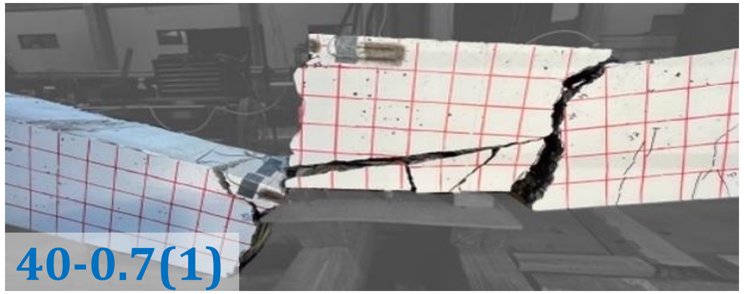

CC-1.5(1)

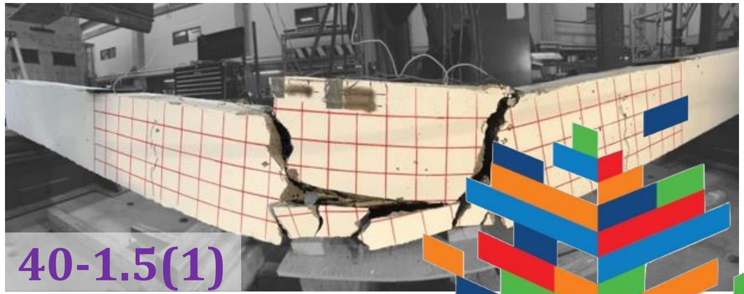

80-0.7(1)


80-1.5(1)


60-0.7(1)

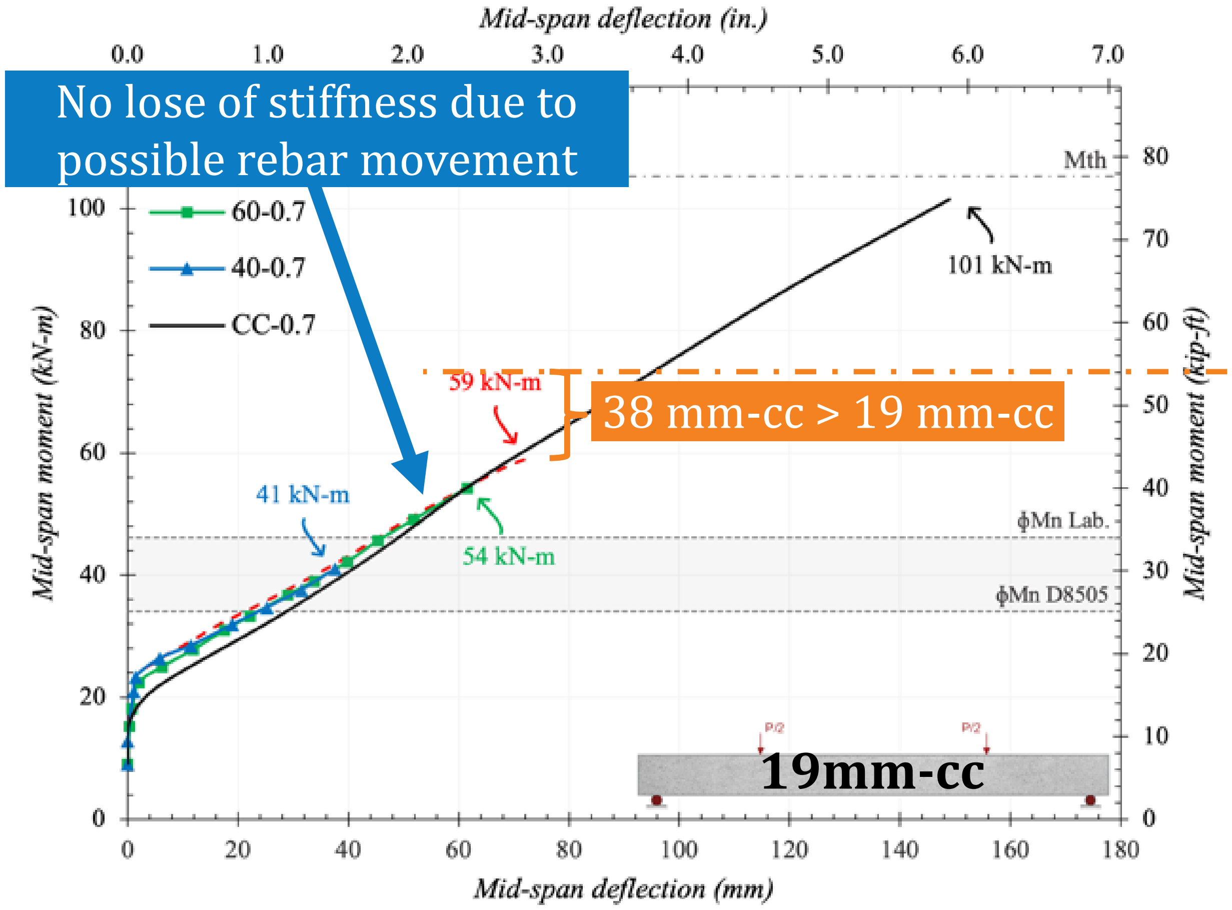

60-1.5(1)

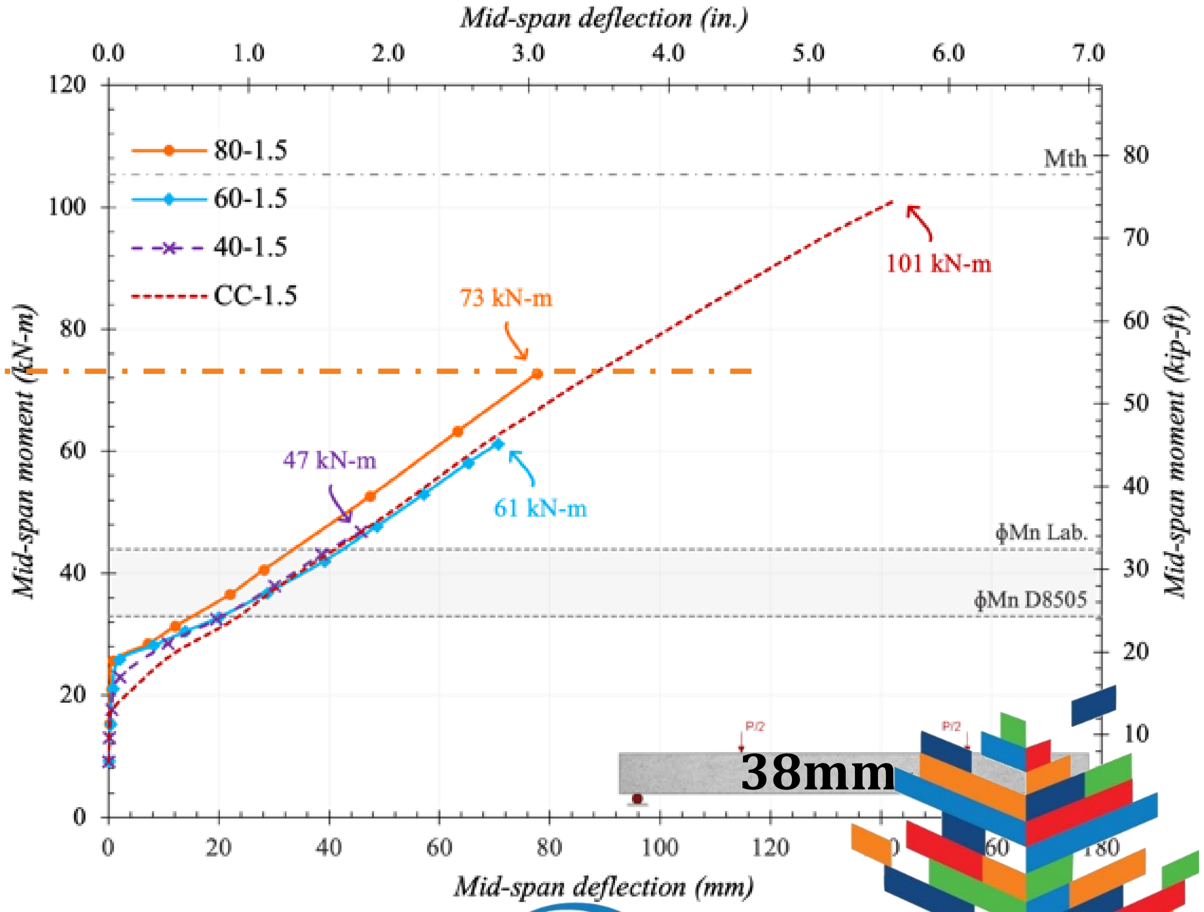

40-0.7(1)


40-1.5(1)

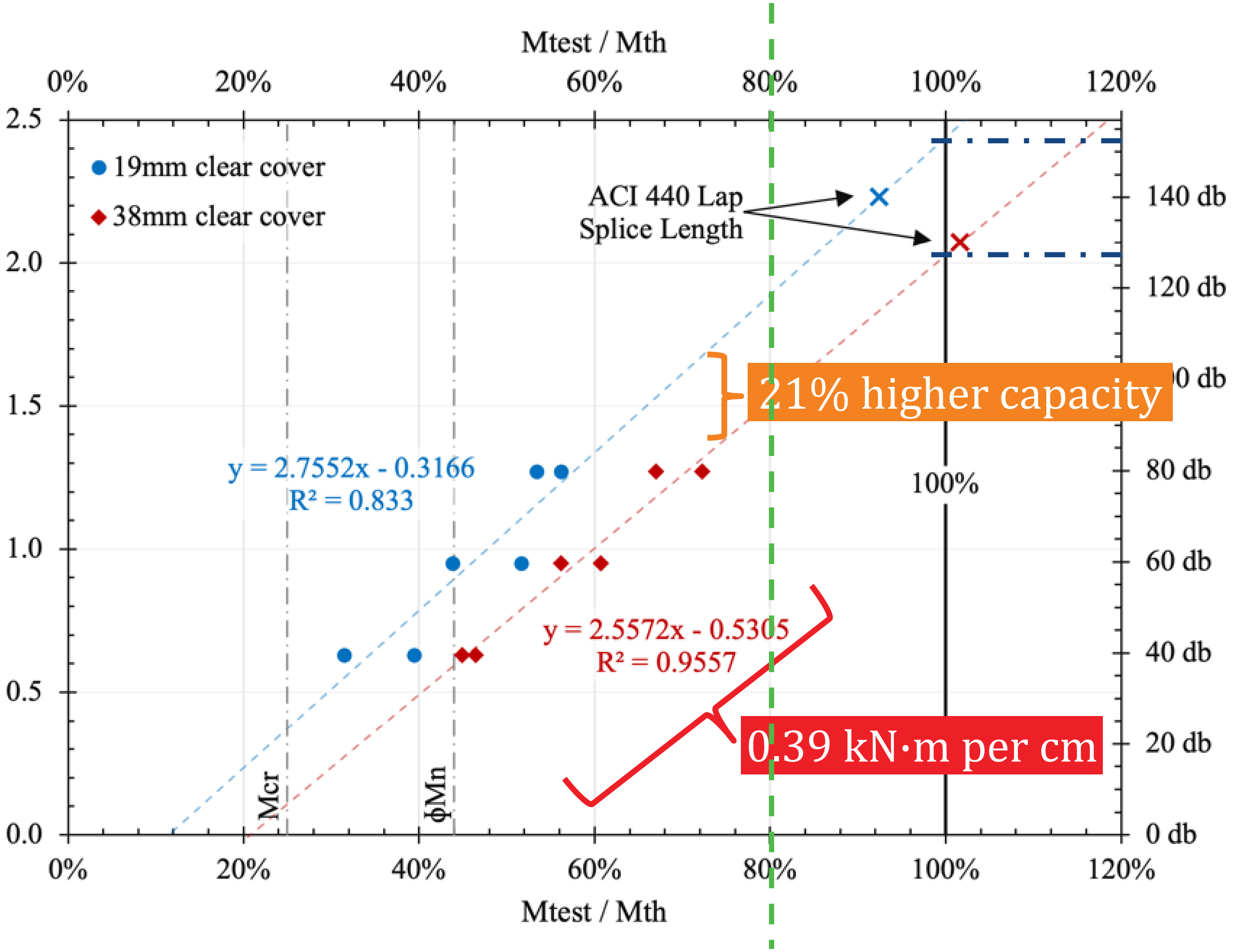
Moment-Deflection Curves

Excessive deflection ≠ Bond failure





Influence of parameters



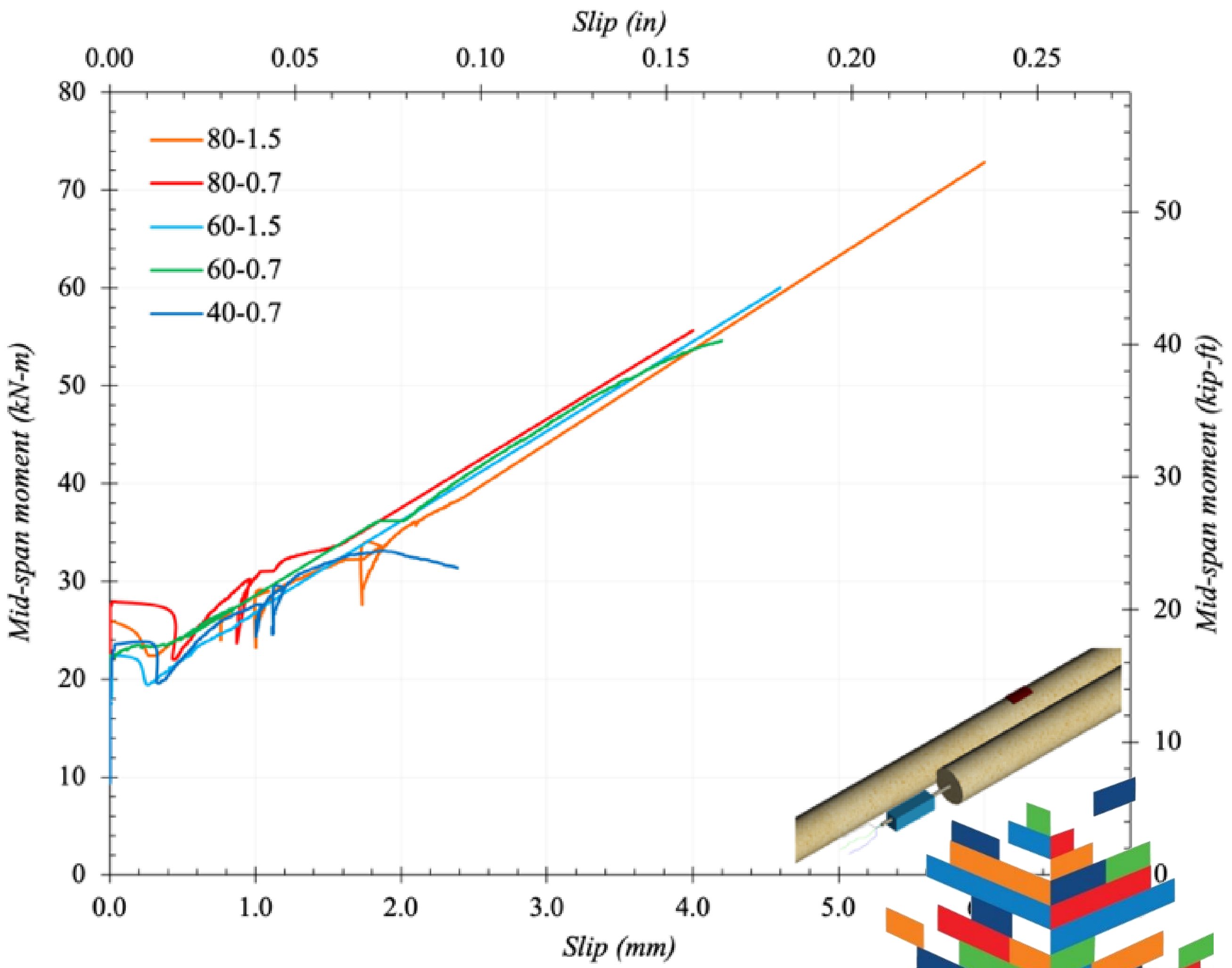
- The impact of the concrete clear cover was evident but there were **not enough data** points to correlate the changes in capacity.
- Assuming a linear relationship, an average increment ratio of **0.39 kN·m per cm** was observed.
- Following this trend, the 100% capacity would be attained with lap splice lengths of **153d_b** and **127d_b** for the 19-cc and 38-cc specimens.
- The expression given by Wambeke and Shield is not enough for achieving the full rebar capacity.
- 153d_b and 127d_b represent changes of **10%** and **-2%**, respectively, when compared to the ACI 440.11-22 provisions for full rebar strength.

Slippage

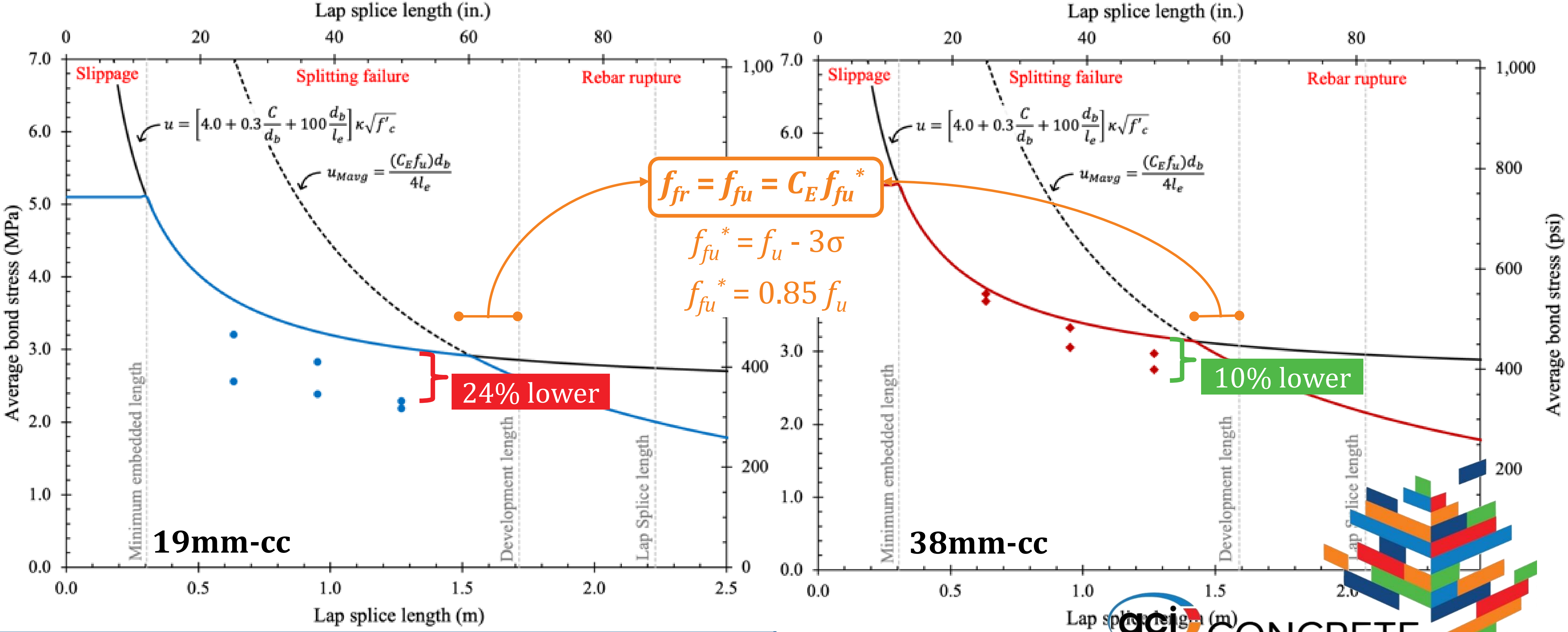
- The graph shows **continuous movement** of the rebar after the initial beam cracking.

- The rebar slippage **did not significantly impact** its bond stress transfer capacity until experiencing a maximum slippage.

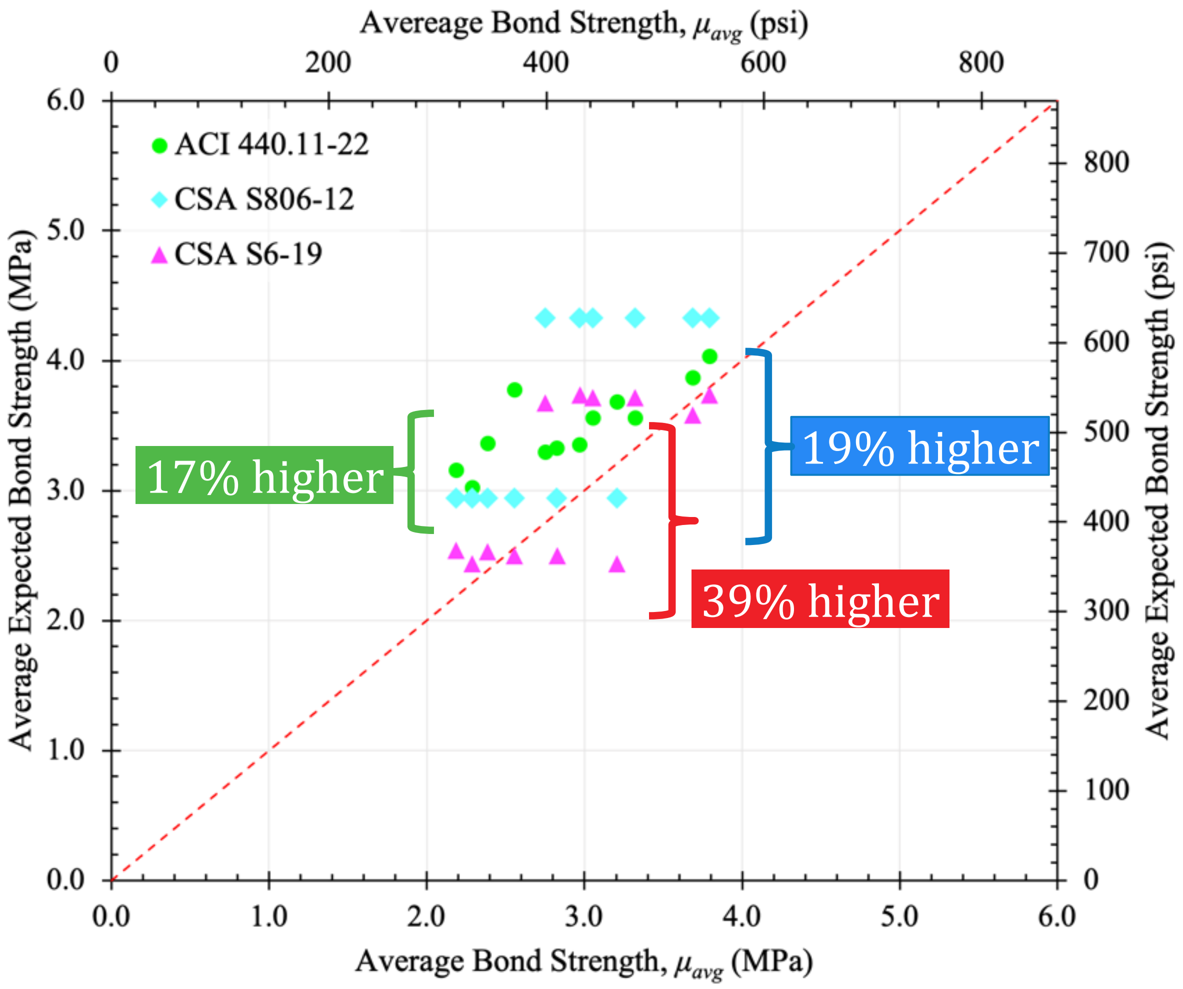
- Potentiometer readings suggests smaller slippage values with decreasing splice length. Generally, longer lap splice lengths allow for **greater rebar movement** before experiencing brittle failure.



ACI 440.11-22 Expression



ACI 440.11-22 Expression



Design and construction of building structures with fibre-reinforced polymers (S806-12)

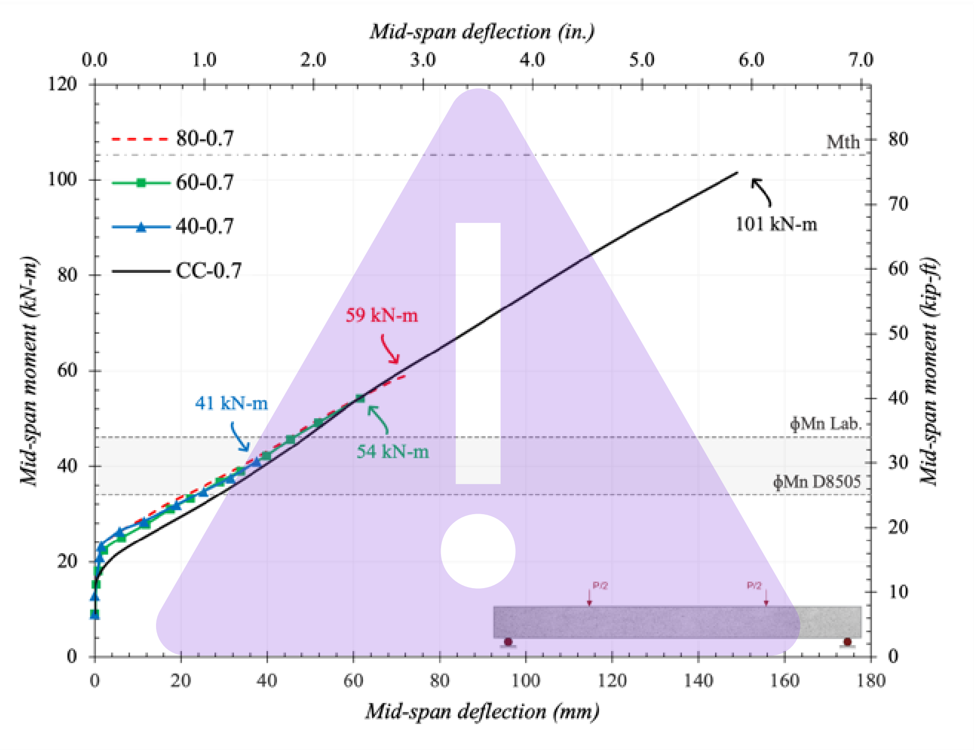
$$\mu_{S806} = \frac{d_{cs}\sqrt{f'_c}}{1.15(k_1 k_2 k_3 k_4 k_5)\pi d_b}$$

Canadian Highway Bridge Design Code, CSA S6-19

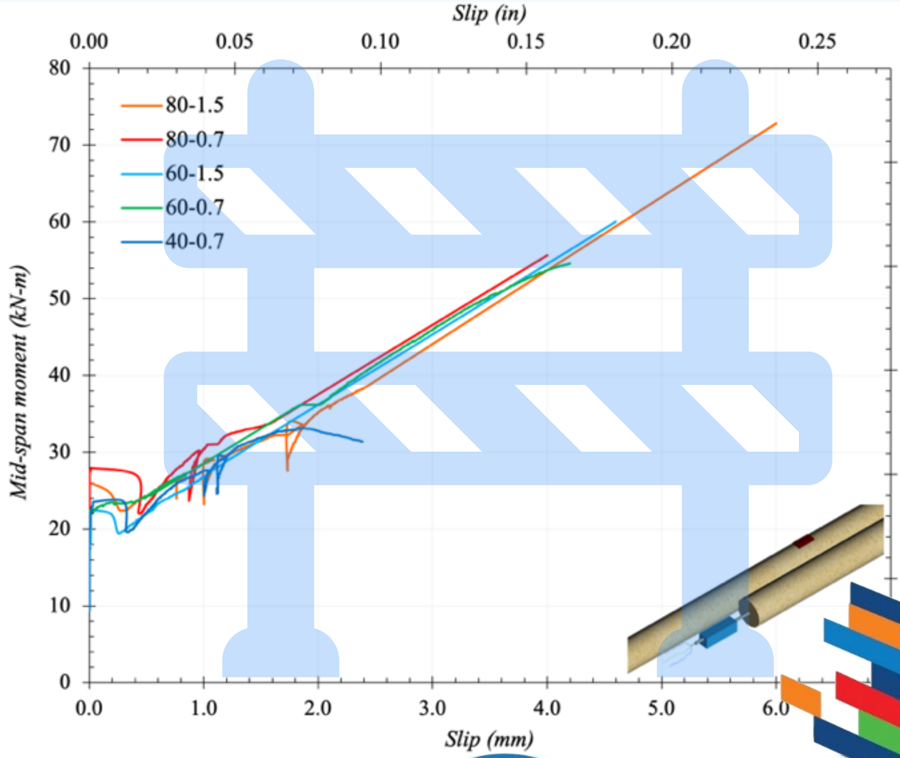
$$\mu_{S6-19} = \frac{f_{cr}\left(d_{cs} + K_{tr}\ E_f/E_s\right)k_6}{0.45\pi d_b k_1}$$

$$where\ \ K_{tr} = \frac{38\ A_{tr}}{sn}$$

Conclusions



Rebar slippage in lap-spliced specimens **had a limited impact** on bond stress transfer capacity and member flexural stiffness until reaching **maximum slippage**. Longer lap splice lengths allowed for **greater rebar movement** before experiencing brittle failure.

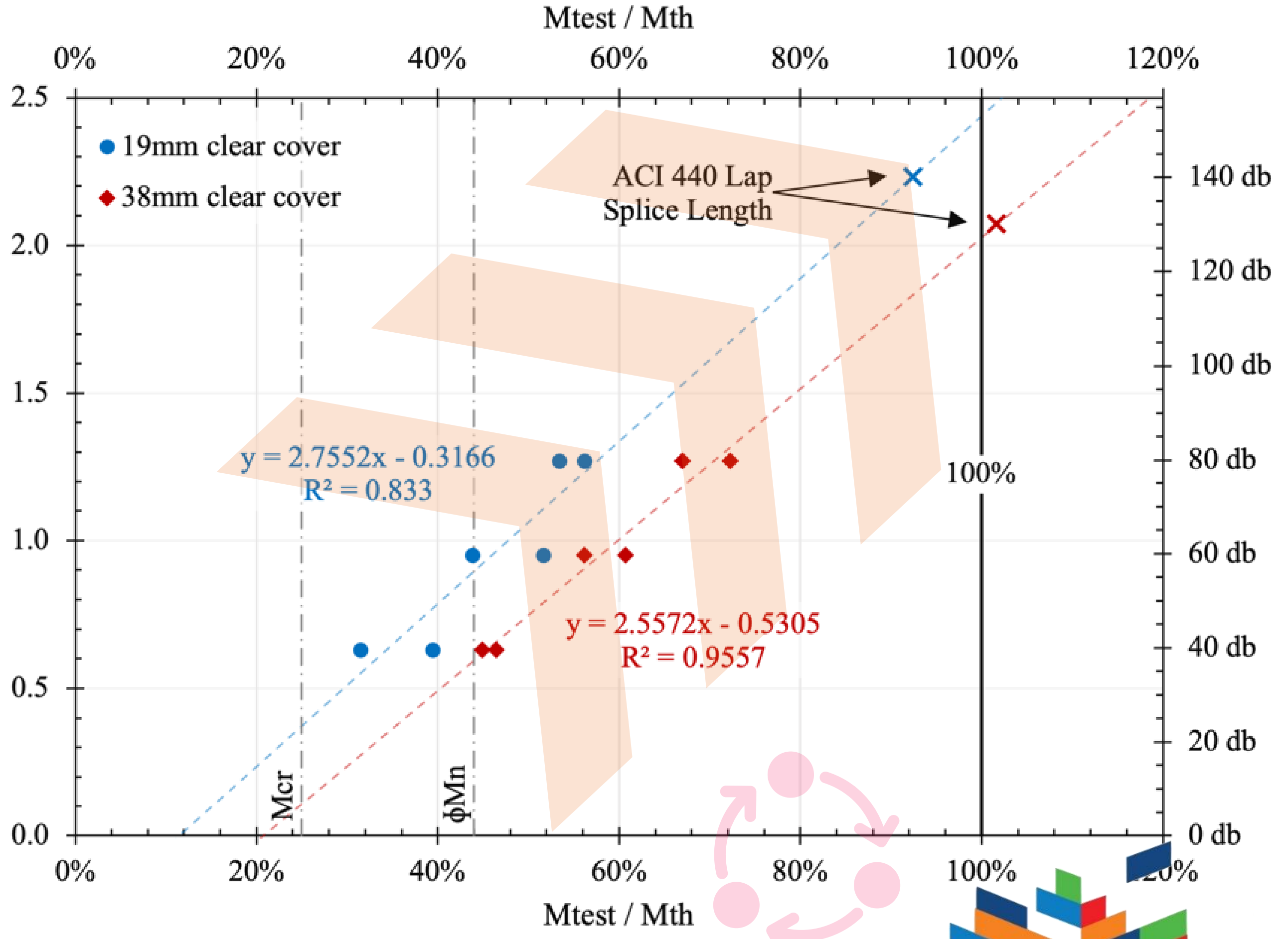


Lap-spliced and un-spliced beams exhibited **similar deflection levels** under the same applied load. This suggests that excessive deflection may not be **an early indicator** of bond failure in GFRP-RC beams.

Conclusions

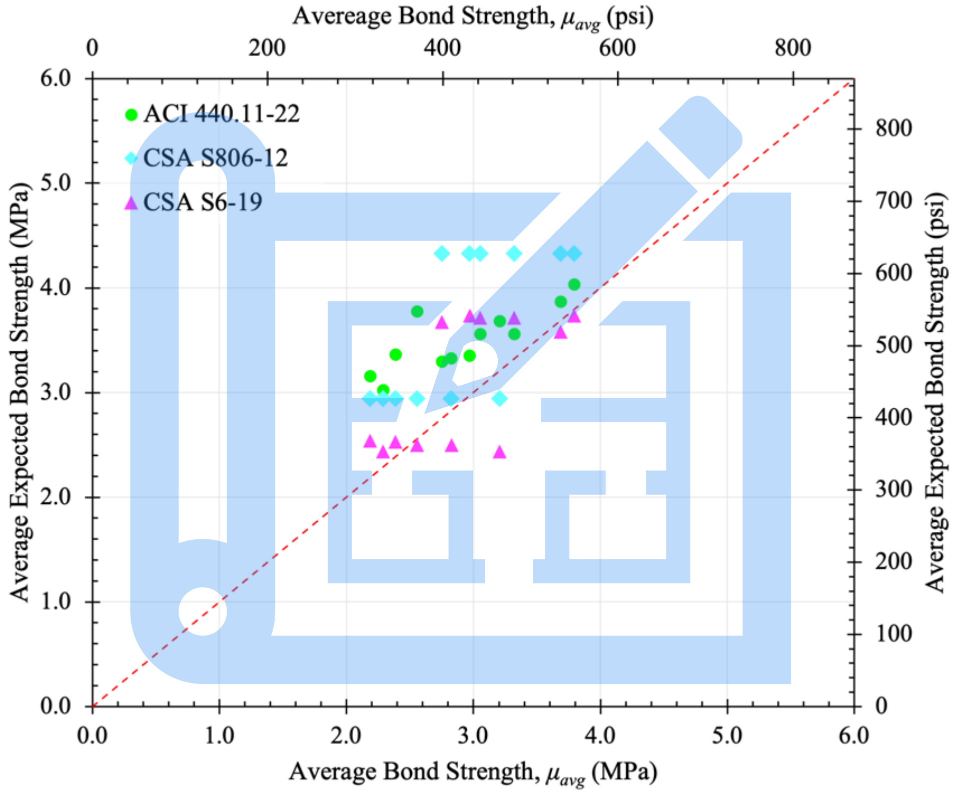
Concrete cover **significantly influenced** the behavior of lap-spliced GFRP-RC beams. The smaller concrete cover in lap-spliced specimens made the 19mm-cc more **susceptible to splitting cracks**, resulting in lower load-bearing capacity compared to 38mm-cc, which exhibited an average **21% higher capacity**.

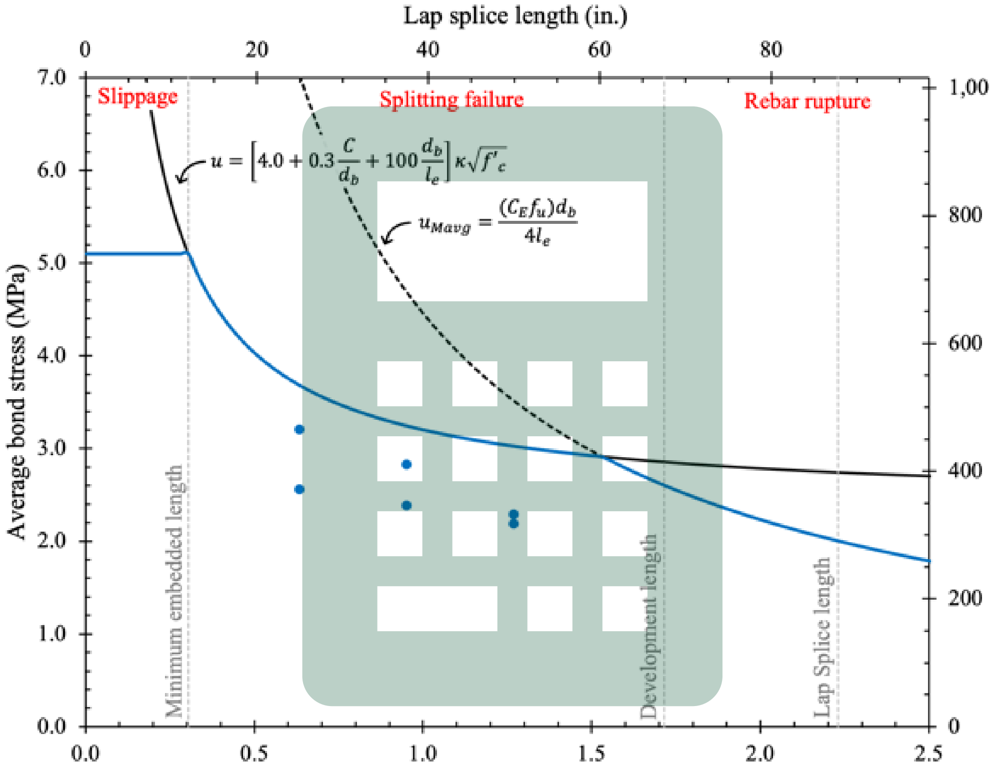
Reaching 100% capacity would have required longer lap splice lengths than those recommended by ACI 440.11-22 provisions. However, **accounting for all strength factors**, lap splice lengths of $119d_b$ and $95d_b$ were estimated for 19- and 38mm-cc, respectively, **representing reductions of 15% and 27% from ACI provisions**.



Conclusions

Both CSA S806-12 and CSA S6-19 showed overpredictions, averaging **19%** and **4%** higher bond strength, respectively. **These discrepancies suggest that current equations may not reliably predict bond capacity for lap-spliced GFRP rebars**.





For 19mm-cc, the ACI expression overpredicted bond strength by an average of **24%**, while for 38mm-cc, it overpredicted by **10%**.

Future Work

- Due to the availability of various GFRP rebars on the market with different ultimate **tensile strength, tensile modulus of elasticity, and surface treatments**, new research campaigns could be focused on assessing the effects of these parameters on bond strength.

- Further research could address the concrete compressive strength and its properties as a material. This would allow for the evaluation of additional parameters such as the impact of **lightweight concrete**, ultra-high-performance concrete (**UHPC**), and fiber reinforced concrete (**FRC**).

- Research campaigns involving **GFRP stirrups** need to be conducted to assess the effect of this transverse reinforcement material.

- A **revised expression** incorporating these parameters needs to be formulated.

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Thank U

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