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# Analysis and Design Issues in Liquid-Containing Concrete Structures

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## CRACK CONTROL IN TWO-WAY REINFORCED CONCRETE PANELS

By
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Presenter: Armin Ziari
**Ryerson University & Candu Energy Inc.**

## OUTLINE

- Research Significance and Scope
- Proposed Crack Prediction Model
- Experimental Program
- Verification
- Design Guide
- Conclusions
- Acknowledgements

## SIGNIFICANCE OF CRACK CONTROL

- Serviceability: Deflection control, Leakage control, …
- Durability: Permeability reduction, Corrosion reduction, …
- Appearance

## SHORTCOMINGS OF CURRENT DESIGN CODES

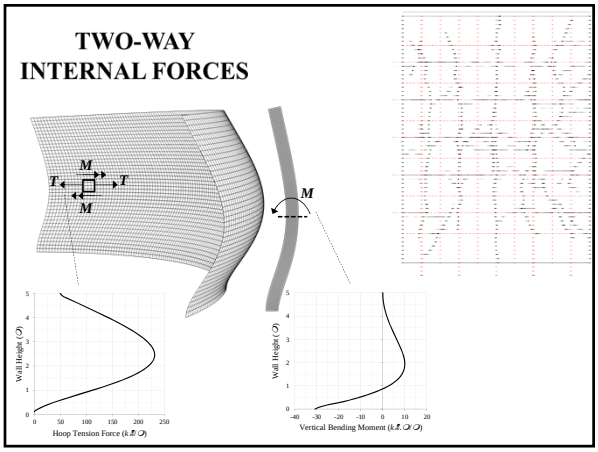
- Simple loading conditions: Pure bending, pure tension,…
- No reliable crack control for two-way members
- Ignoring repeated loading effects
- Ignoring long term effects

## SCOPE OF RESEARCH

- Experimentally investigating the cracking and leakage behaviour of two-way panels
- Using FE technique to understand different aspects of RC cracking
- Developing a new analytical crack prediction model for two-way panels

## TWO-WAY ELEMENTS

## TWO-WAY INTERNAL FORCES




## PROPOSED CRACK PREDICTION ANALYTICAL MODELS

STABILIZED CRACKING LOAD

$$N_{rx} = \left(f_{ctm}(t) - \beta_{spy}\sigma_{spy} - \sigma_{csx}\right)A_{c,efx}\left(1+\alpha_e\rho_{s,efx}\right)$$

MINIMUM CRACK SPACING

$$S^{II}_{\min x} = \frac{\left(d_{t,efx} - d_{by}\right)s_x}{\alpha_{sp}\beta_b\tau_{tpx}\pi d_{bx}}\left(f_{ctm} - \beta_{spy}\sigma_{spy} - \sigma_{csx}\right)$$

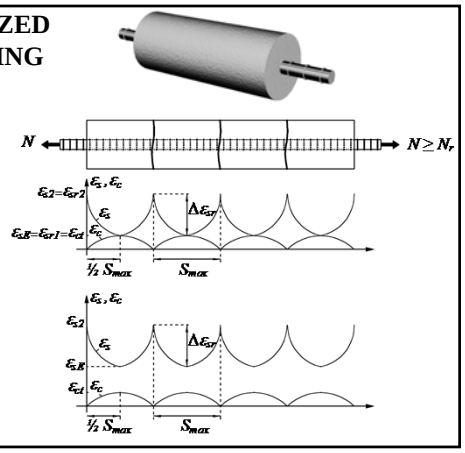
MAXIMUM CRACK SPACING

$$S^{II}_{\max x} = \text{larger of}\begin{cases} s_y + S^{II}_{\min x} \\ 2S^{II}_{\min x} \end{cases} < S^{I}_{\max x}$$

MAXIMUM CRACK WIDTH AT STABILIZED CRACKING

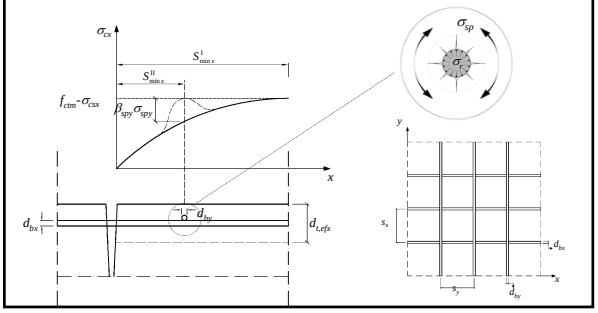
$$w_{\max x} = \beta_{gx} S^{II}_{\max x}\left(\varepsilon_{smx} - \varepsilon_{cmx} - \varepsilon_{cs}\right)$$

## STABILIZED CRACKING

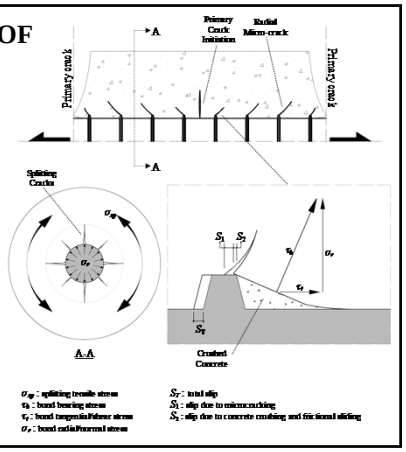



## STABILIZED CRACKING LOAD

$$N_{rx} = \left(f_{ctm}(t) - \beta_{spy}\sigma_{spy} - \sigma_{csx}\right)A_{c,efx}\left(1+\alpha_e\rho_{s,efx}\right)$$



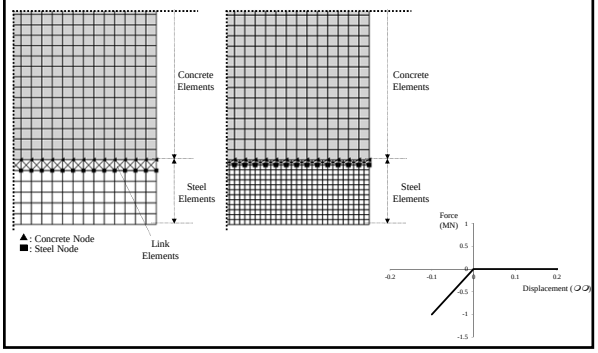
## MECHANISM OF BOND



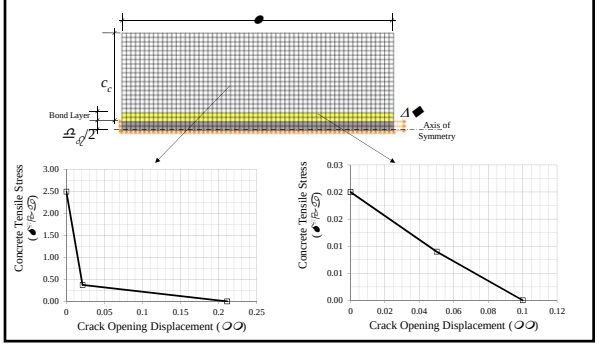

$\sigma_{sp}$ : splitting tensile stress
$\tau_b$ : bond bearing stress
$\tau_r$ : bond tangential/shear stress
$\sigma_r$ : bond radial/normal stress

$S_T$ : total slip
$S_1$ : slip due to micro-cracking
$S_2$ : slip due to concrete crushing and frictional sliding

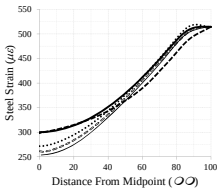
## DIAGONAL LINK ELEMENTS



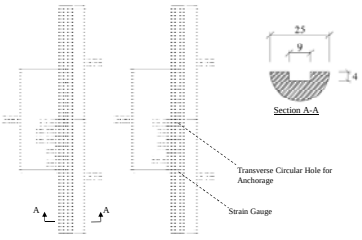

## BOND LAYER MODEL

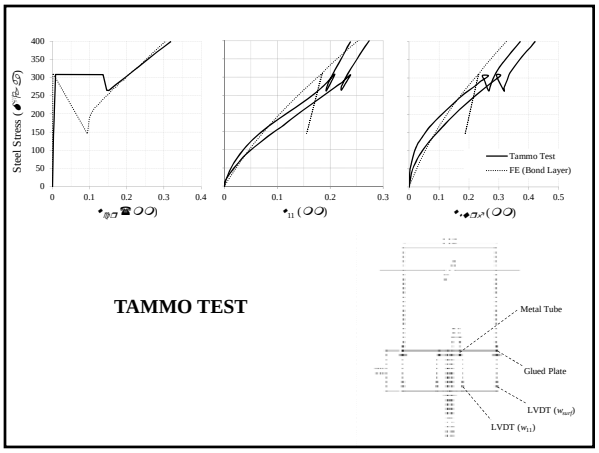



## VERIFICATION OF BOND MODELS

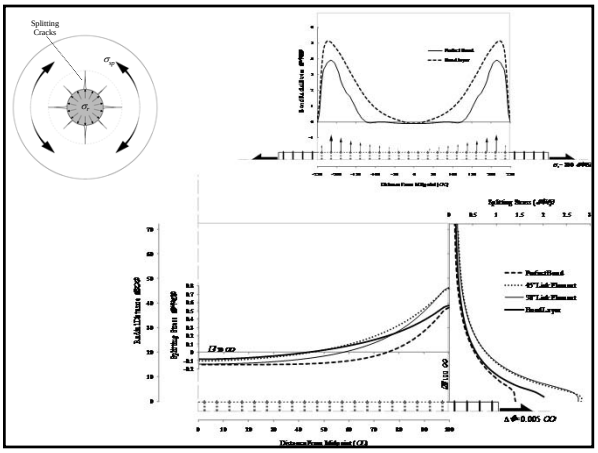



### KANKAM TEST

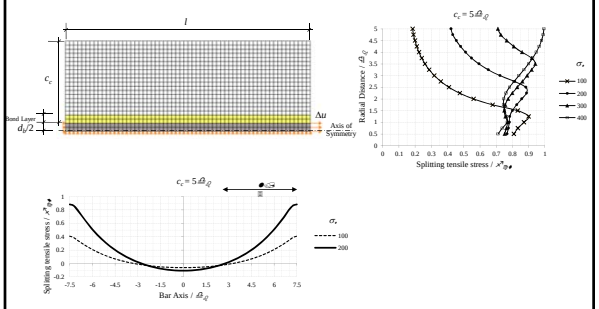



### TAMMO TEST



## SPLITTING STRESSES

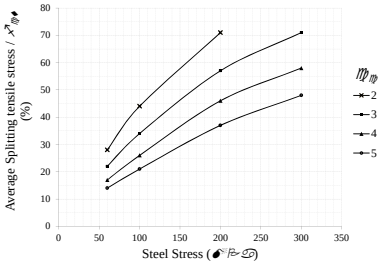



## AVERAGE SPLITTING STRESSES

$$N_{rx} = \left(f_{ctm}(t) - \beta_{spy}\sigma_{spy} - \sigma_{csx}\right)A_{c,efx}\left(1+\alpha_e\rho_{s,efx}\right)$$

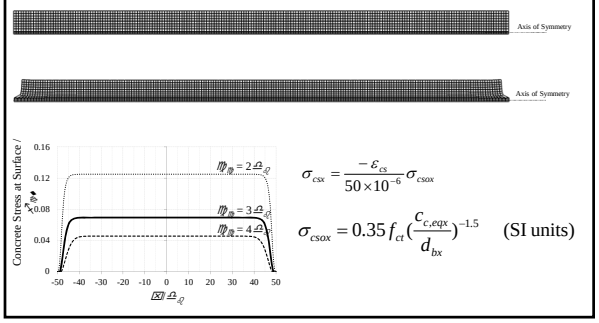
$$\sigma_{spy} = f(f_{ct}, c_{cy}/d_{by}, \sigma_{sy,crx})$$

$$\beta_{spy} \cong \frac{2}{3}\times\frac{2c_{cy}}{d_{t,efx}} \le \frac{2}{3}$$




## SHRINKAGE INDUCED TENSILE STRESSES

$$N_{rx} = \left(f_{ctm}(t) - \beta_{spy}\sigma_{spy} - \sigma_{csx}\right)A_{c,efx}\left(1+\alpha_e\rho_{s,efx}\right)$$

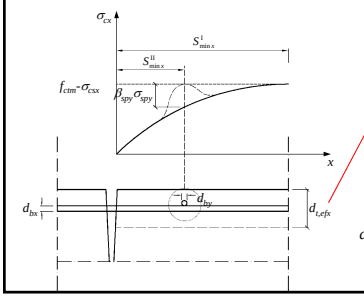



$$\sigma_{csx} = \frac{-\varepsilon_{cs}}{50\times10^{-6}}\sigma_{csox}$$

$$\sigma_{csox} = 0.35 f_{ct}\left(\frac{c_{c,eqx}}{d_{bx}}\right)^{-1.5} \quad \text{(SI units)}$$

## EFFECTIVE TENSION AREA

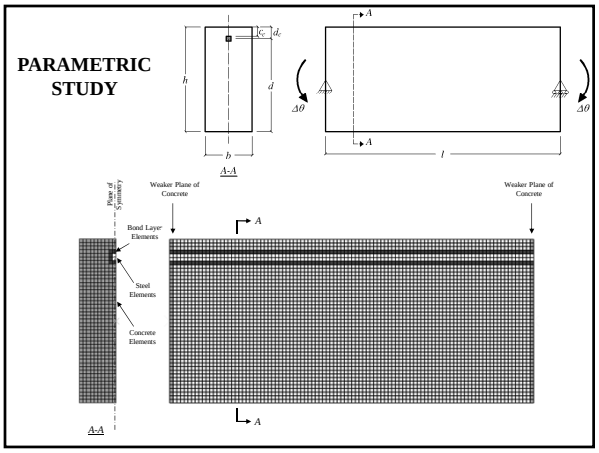
$$N_{rx} = \left(f_{ctm}(t) - \beta_{spy}\sigma_{spy} - \sigma_{csx}\right)A_{c,efx}\left(1+\alpha_e\rho_{s,efx}\right)$$

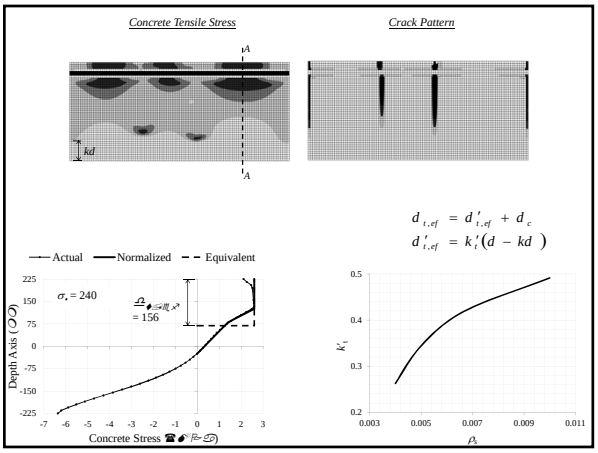



$$A_{c,efx\,(\text{per bar})} = \left(d_{t,efx} - d_{by}\right)s_x$$

$$d_{t,efx} = \begin{cases} \text{for direct tension cracks,} \\ \quad \text{lesser of } [2.5d_{cx}, 0.5h] \\ \text{for flexural cracks,} \\ \quad k'_{tx}(d_x - kd_x) + d_{cx} \end{cases}$$

## PARAMETRIC STUDY

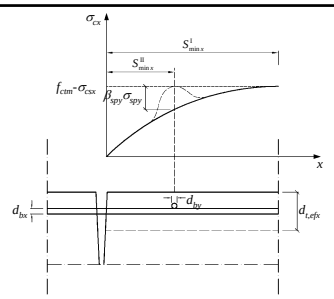



$$d_{t,ef} = d'_{t,ef} + d_c$$

$$d'_{t,ef} = k'_t(d - kd)$$

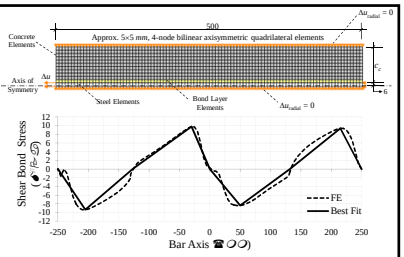
## MINIMUM CRACK SPACING

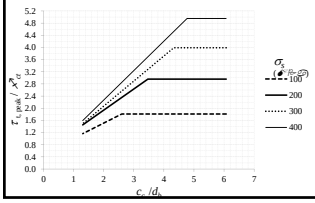


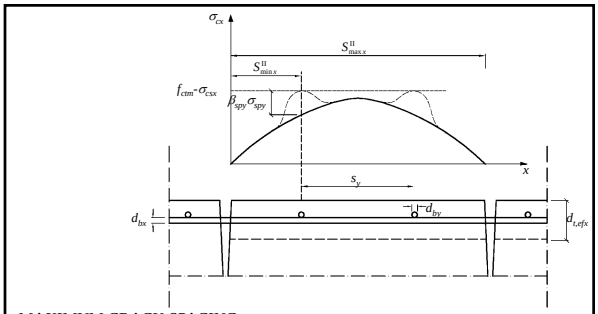
$$S^{II}_{\min x} = \frac{(d_{t,efx} - d_{by})s_x}{\alpha_{sp}(\beta_b \tau_{tpx} \pi d_{bx})}\left(f_{ctm} - \beta_{spy}\sigma_{spy} - \sigma_{csx}\right)$$

$$S^{I}_{\min x} = \frac{d_{t,efx} s_x}{\alpha_{sp}\beta_b \tau_{tpx} \pi d_{bx}}\left(f_{ctm} - \sigma_{csx}\right)$$

## BOND SHEAR STRESS





MAXIMUM CRACK SPACING

$$S^{II}_{\max x} = \text{lesser of} \begin{cases} s_y + 2S^{II}_{\min x} \\ S^{I}_{\max x} = 2S^{I}_{\min x} \end{cases} \quad \text{(low probability)}$$

$$S^{II}_{\max x} = \text{larger of} \begin{cases} s_y + S^{II}_{\min x} \\ 2S^{II}_{\min x} \end{cases} < S^{I}_{\max x} \quad \text{(high probability)}$$

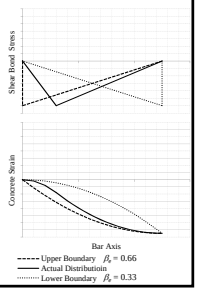
MAXIMUM CRACK WIDTH AT STABILIZED CRACKING

$$w_{\max x} = \beta_{gx} S^{II}_{\max x}\left(\varepsilon_{smx} - \varepsilon_{cmx} - \varepsilon_{cs}\right)$$

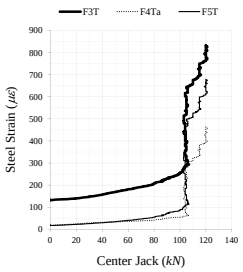
$$\beta_{gx} = \begin{cases} \dfrac{h - kd_x}{d_x - kd_x} & \text{Flexural cracks} \\ 1 & \text{Direct Tension Cracks} \end{cases}$$

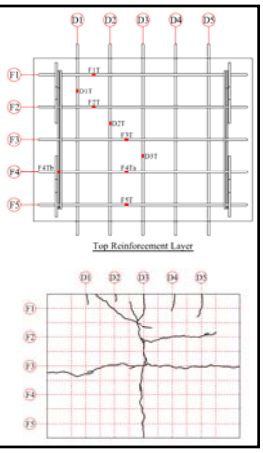
$$\varepsilon_{smx} - \varepsilon_{cmx} = \varepsilon_{s2x} - \beta_e \Delta\varepsilon_{sx}\left(1 + \alpha_e \rho_{s,efx}\right)$$

$$\Delta\varepsilon_{sx} = \frac{2\alpha_{sp}\beta_b \tau_{tpx} S^{II}_{\max x}}{E_s d_{bx}}$$

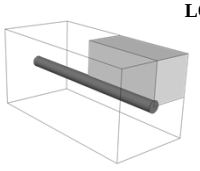


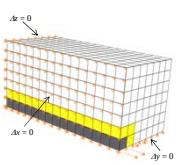

## REDUCTION OF BOND STRENGTH DUE TO SPLITTING CRACKS

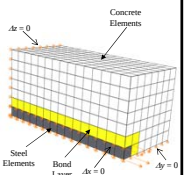


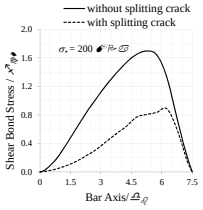




## BOND STRENGTH REDUCTION DUE TO LONGITUDINAL SPLITTING CRACKS







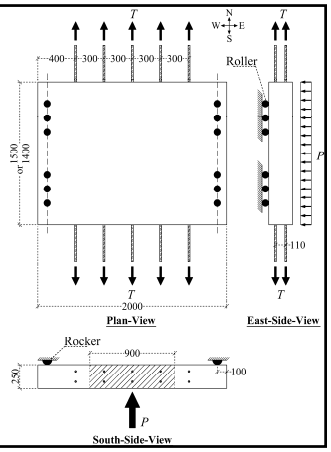




$$\alpha_{sp} = \frac{\tau_{tp,sp}}{\tau_{tp}}$$

| $c_c/d_b$ | $l/d_b$ | $\tau_{tp,sp}/\tau_{tp}$ (%) $\sigma_s$ (MPa) 100 | 200 |
|---|---|---|---|
| 2 | 15 | 45 | 60 |
| 3 | 15 | 58 | 52 |
| 4 | 15 | 67 | 57 |
| 4 | 30 | 49 | 46 |
| 5 | 30 | 58 | 55 |

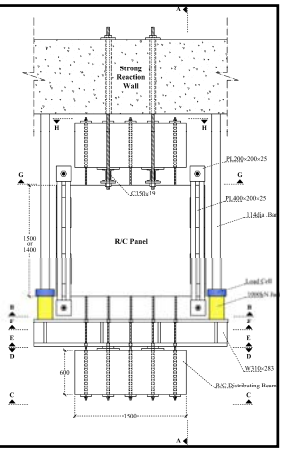
## EXPERIMENTAL PROGRAM

**LOADING SCHEME**



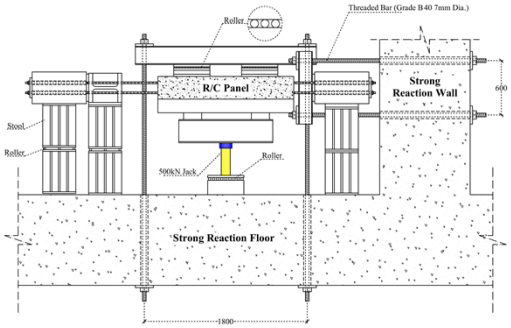

## SCHEMATIC OF TEST SETUP

**(PLAN-VIEW)**



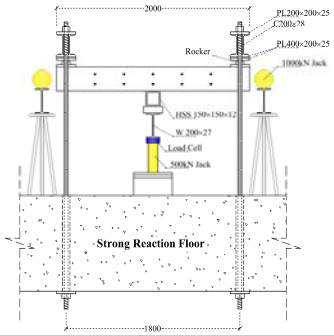

## SCHEMATIC OF TEST SETUP

**(EAST-SIDE-VIEW)**

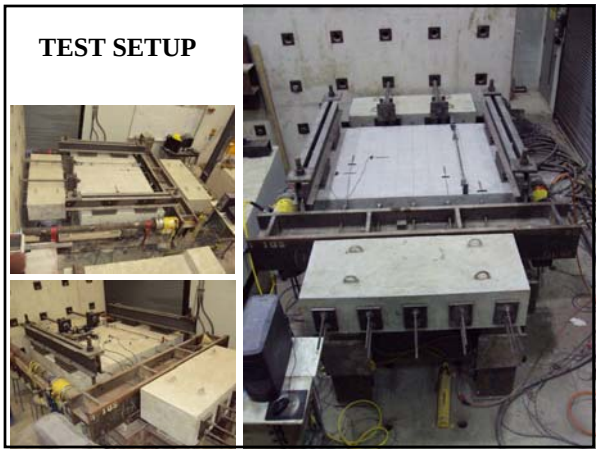



## SCHEMATIC OF TEST SETUP

**(SOUTH-SIDE-VIEW)**




## TEST SETUP



## VERIFICATION

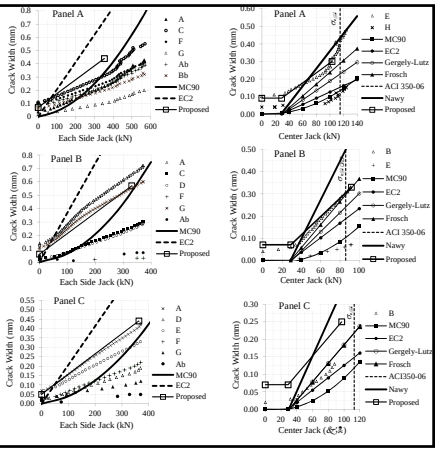
### STABILIZED CRACKING LOAD

| Panel | $E_s$, GPa | $E_c$, MPa | $f_{ct}$, MPa | $\varepsilon_{cs}$, με | Stabilized Cracking Load (kN) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Direct Tension Crack | | | | | Flexural Crack | | | |
| | | | | | Experiment (total side jacks) | One-Way | | Two-Way | | Experiment (center Jack) | One-Way | | Two-Way | |
| | | | | | | MC90 | Error (%) | Proposed Model | Error (%) | | MC90 | Error (%) | Proposed Model | Error (%) |
| A | 200 | 34000 | 2.97 | -141 | 756 | 1166 | 54 | 707 | -7 | 92 | 167 | 82 | 103 | 12 |
| B | 200 | 35000 | 2.79 | -107 | 708 to 744 | 1078 | 45 to 52 | 662 | -7 to -11 | 88 to 105 | 158 | 50 to 80 | 92 | 5 to -12 |
| C | 200 | 33000 | 2.79 | -113 | 612 to 738 | 1097 | 49 to 79 | 726 | 19 to -2 | 86 | 148 | 72 | 97 | 13 |

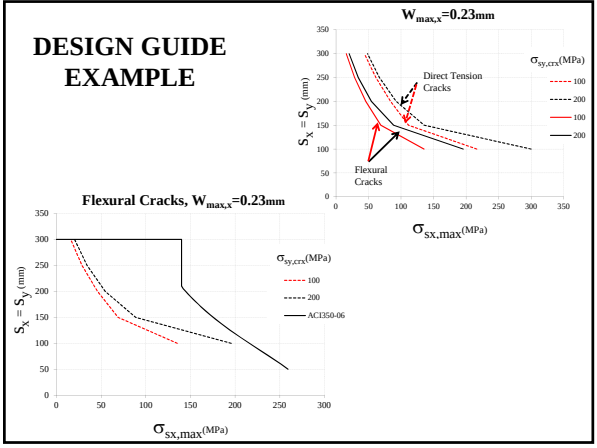
### CRACK SPACING

| Panel | Crack Spacing (mm) (%Error) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MC90 | | EC2 | | Rizk&Marzouk | | Proposed Model | | | | | | Experiment | | | |
| | | | | | | | Low Probability | | | | High Probability | | | | | |
| | $S_{max}$ | $S_{many}$ | $S_{max}$ | $S_{many}$ | $S_{mx}$ | $S_{my}$ | $S^{II}_{minx}$ | $S^{II}_{miny}$ | $S^{II}_{maxx}$ | $S^{II}_{many}$ | $S^{II}_{maxx}$ | $S^{II}_{many}$ | $S^{II}_{minx}$ | $S^{II}_{miny}$ | $S^{II}_{maxx}$ | $S^{II}_{many}$ |
| A | 677 (57) | 374 (-10) | 1033 (140) | 365 (-12) | 503 (39) | 503 (64) | 217 (-27) | 177 (-12) | 652 (52) | 733 (77) | 517 (20) | 477 (15) | 295 | 200 | 430 | 414 |
| B | 833 (11) | 478 (-12) | 1231 (64) | 449 (-17) | 561 (11) | 359 (-11) | 212 (-18) | 168 (-38) | 641 (-15) | 724 (34) | 512 (-32) | 468 (-13) | 260 | 270 | 750 | 540 |
| C | 677 (115) | 306 (-13) | 1033 (228) | 337 (-4) | 511 (81) | 257 (-21) | 237 (-5) | 152 (-49) | 662 (110) | 716 (105) | 474 (50) | 452 (29) | 250 | 300 | 315 | 350 |

**MAXIMUM CRACK WIDTH**




**DESIGN GUIDE EXAMPLE**




## CONCLUSIONS

- New crack prediction model in two-way RC panels that incorporates:
  - New FE parametric studies of:
    - Bond shear and normal stresses
    - Average splitting tensile stresses
    - New factor for effective tension area
    - Shrinkage induced tensile stresses
    - Bond strength reduction due to splitting cracks
- Better agreement with experimental results
- New accurate design guidelines to replace unconservative ACI design guideline

## ACKNOWLEDGEMENTS

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**Ryerson University**

**Candu Energy Inc.**

THANK YOU

**END**