American Concrete Institute

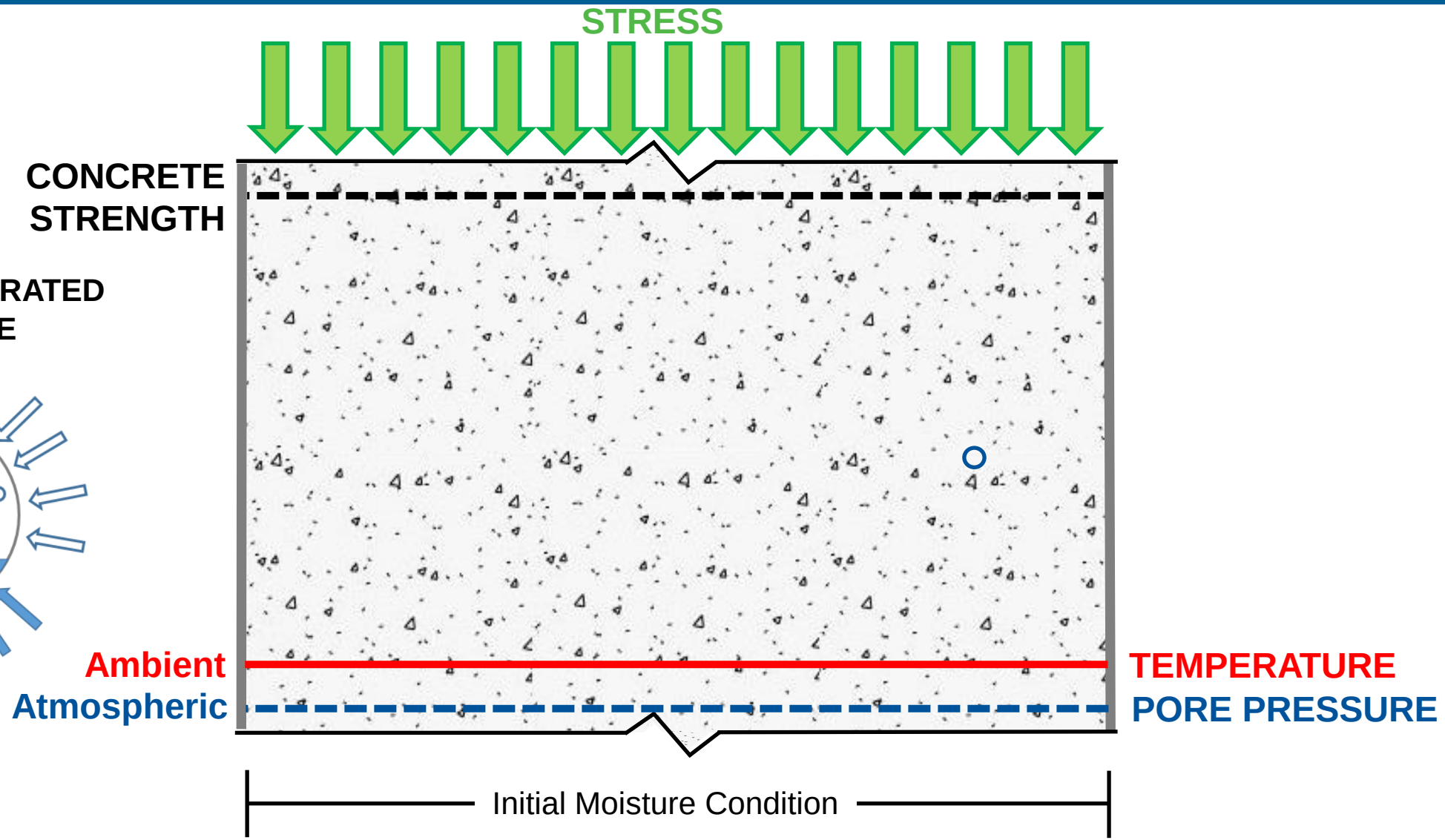
Prediction of Thermally Induced Explosive Concrete Spalling in Normal Weight Concrete under High Intensity Fire Exposure

Aerik Carlton, Spencer Quiel, and Clay Naito

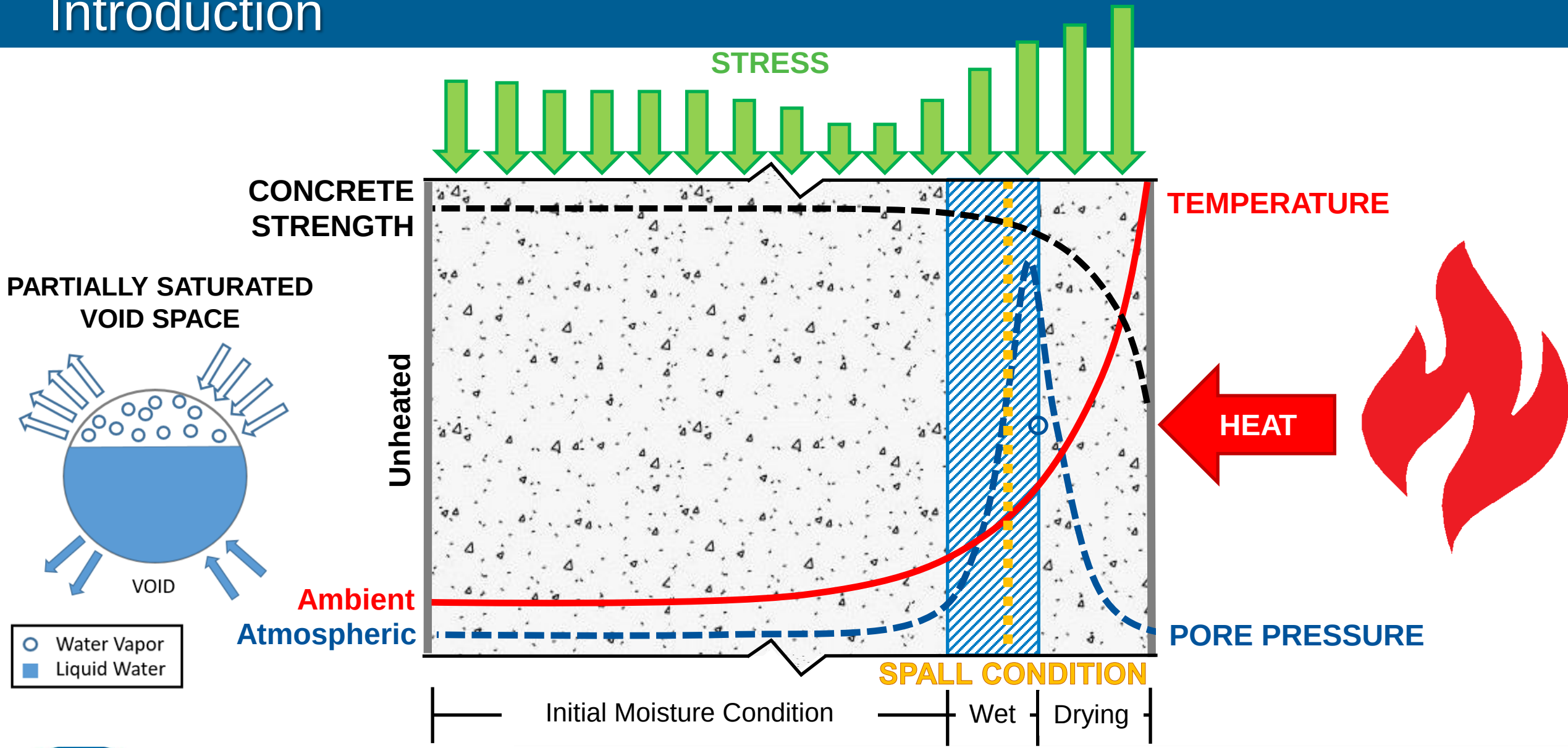
Overview

- Introduction
  - Basic generalization of the behavior
- Analytical Prediction Methodology
  - Detailed method description
  - Validation example
  - Method results and discussion
- Questions

Introduction



Introduction



American Concrete Institute

LEHIGH UNIVERSITY

UNIVERSITY TRANSPORTATION CENTER FOR UNDERGROUND TRANSPORTATION INFRASTRUCTURE

Analytical Prediction Methodology

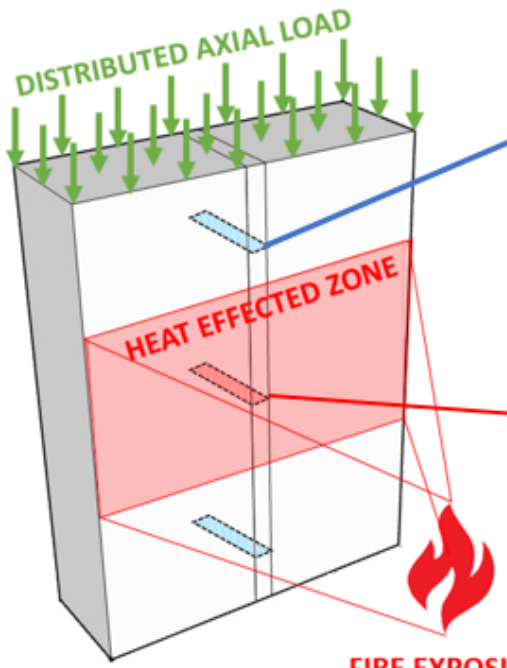
Finite Element Method Analysis Including Thermal Effects

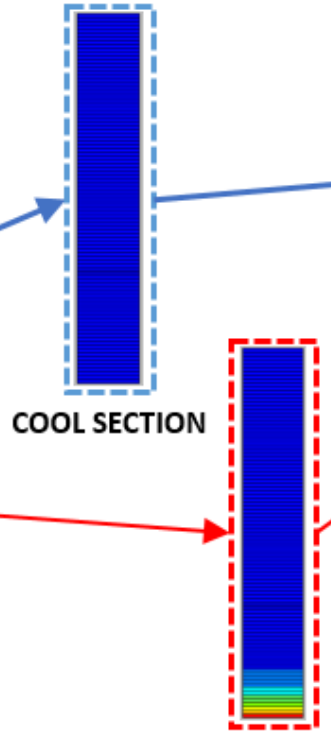
- Temperature Analysis
  - SAFIR-Thermal
  - Experimental Input
- Mechanical Analysis
  - SAFIR-Mechanical

Numerical Computation

- Spall Prediction Analysis
  - MATLAB based

STRUCTURAL CONDITION → TEMPERATURE ANALYSIS → MECHANICAL ANALYSIS → SPALL PREDICTION ANALYSIS



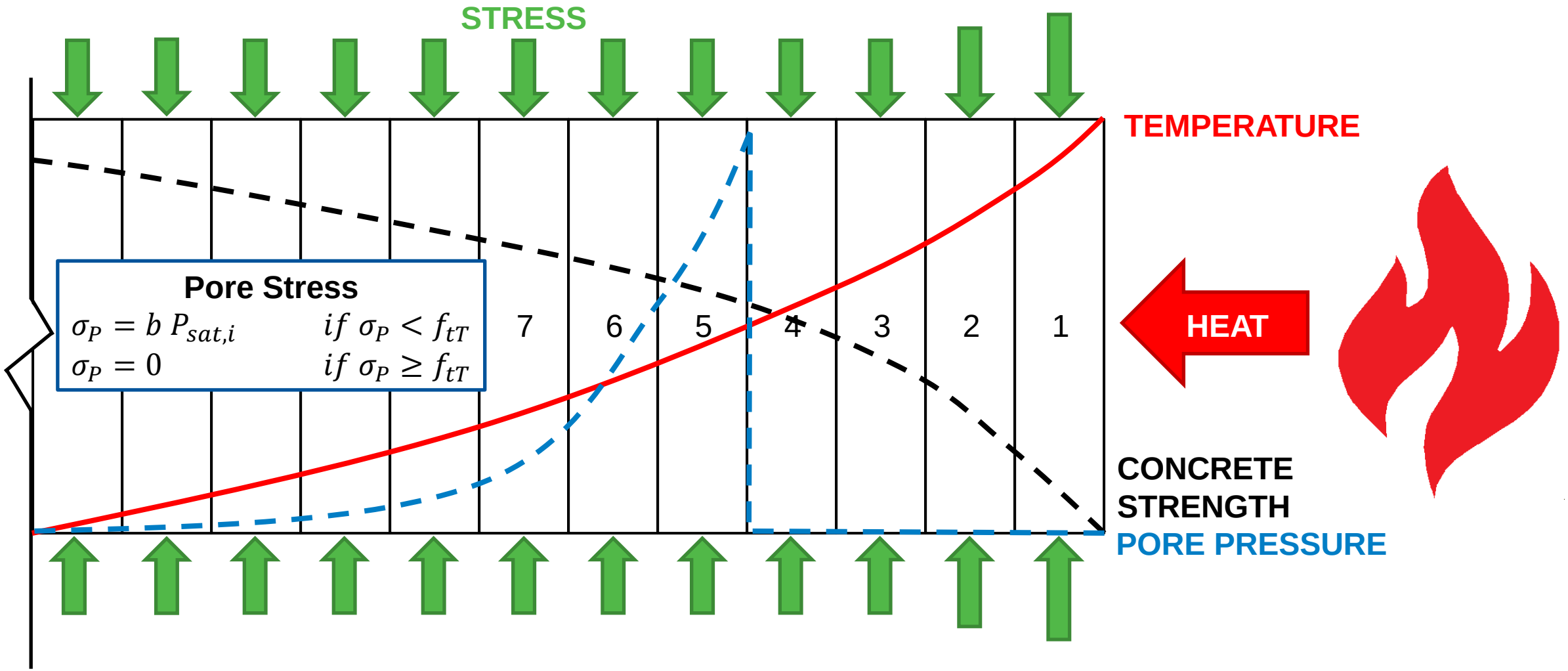


Temperature Analysis Output
$T_i(t)$

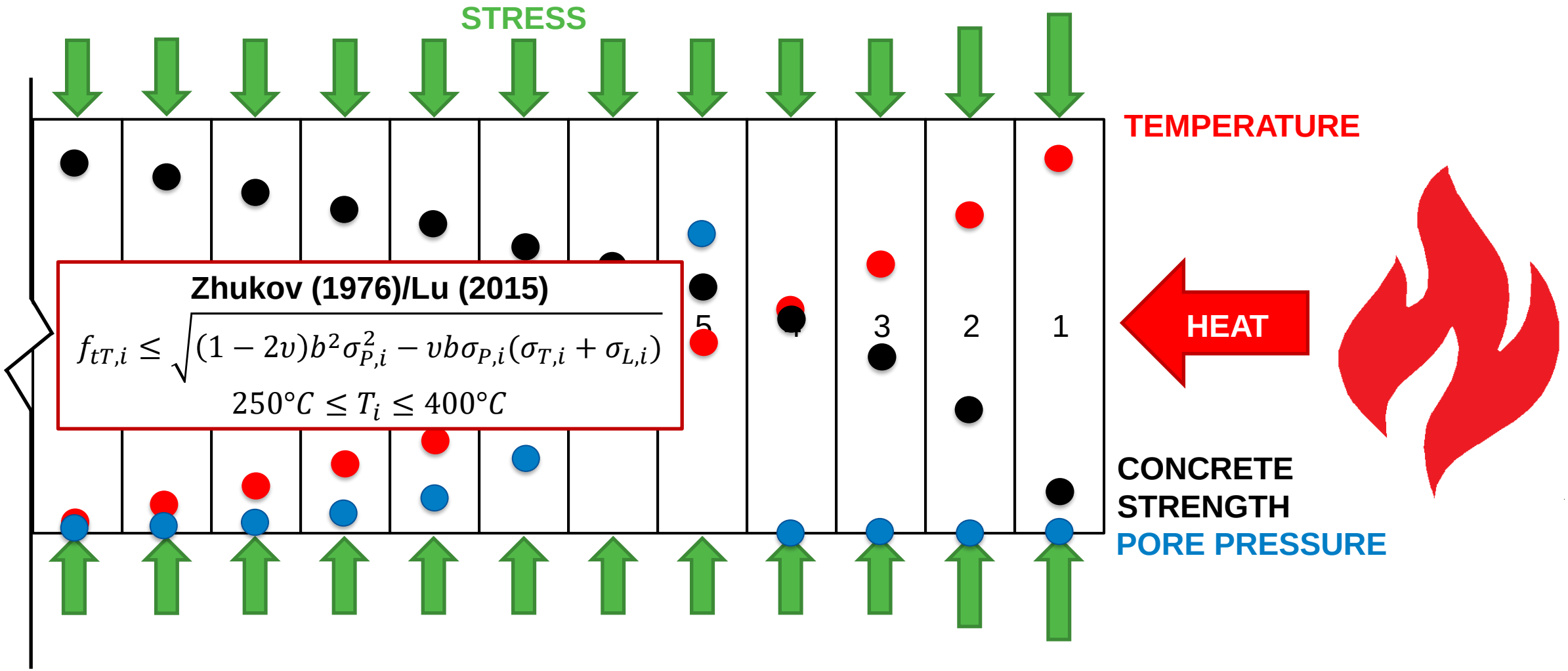
Mechanical Analysis Output
$\sigma_{mech,i}(t) = \sigma_T + \sigma_L$
$\varepsilon_{total,i}(t)$
$E_{tangent,i}(t)$

- Pore Stress
- Tensile Capacity Check
- Secant Modulus
- Spalled Section "Cracked Section" Definition
- Stability Check
- STABILIZED NO SPALL -OR- DESTABILIZED SPALL

Analytical Prediction Methodology



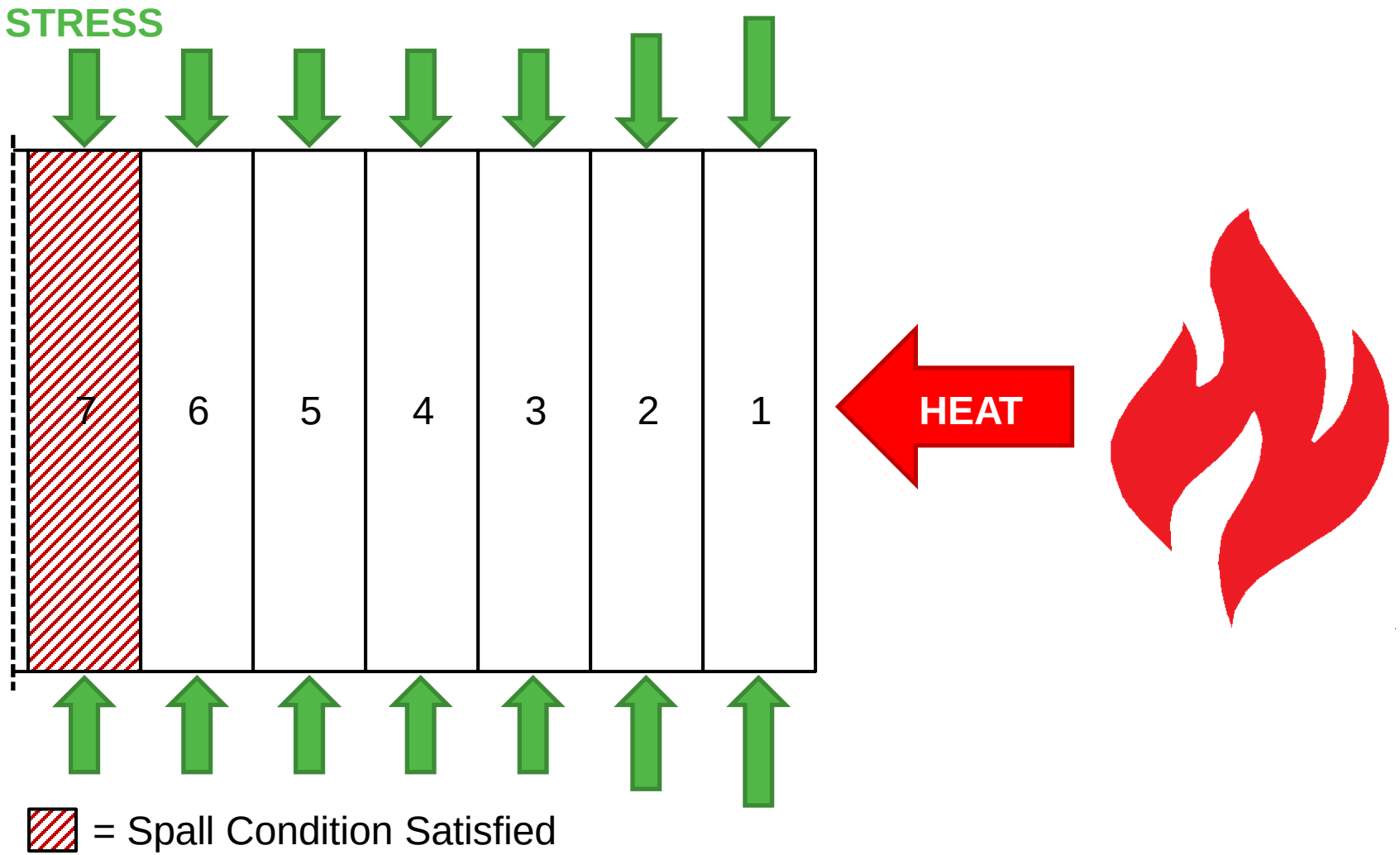
Analytical Prediction Methodology



Analytical Prediction Methodology

Spalled Section "Cracked Section" Definition

Stability Check



Analytical Prediction Methodology

Mechanical Analysis Output

$\sigma_{mech,i}(t) = \sigma_T + \sigma_L$

$\varepsilon_{total,i}(t)$

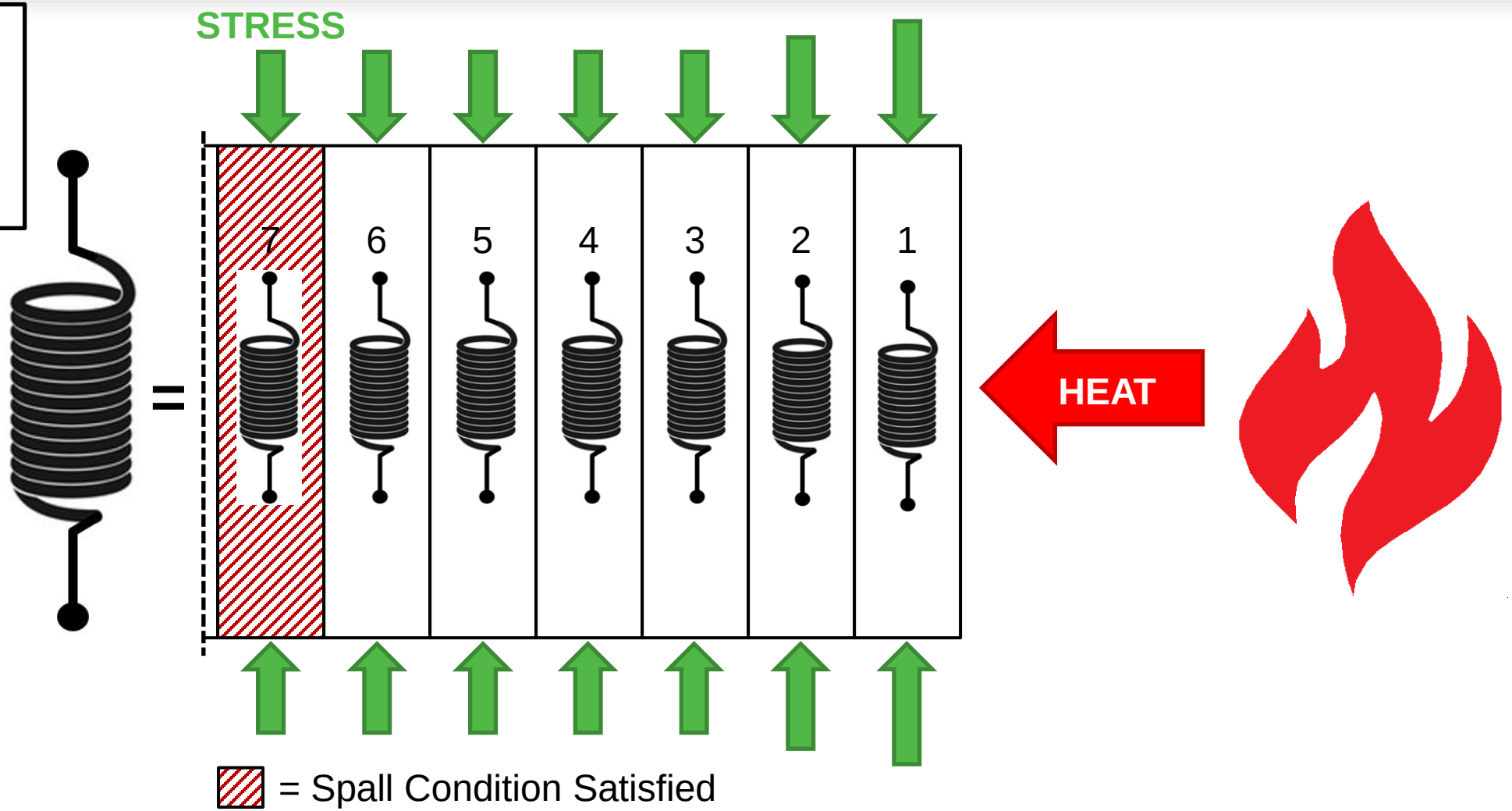
$E_{tangent,i}(t)$

Center of Stiffness

$$y_{EC} = \frac{\sum_1^n E_{secant,n}\, y_n\, A_n}{\sum_1^n y_n A_n}$$

Secant Modulus

$$E_{secant,i} = \frac{\sigma_{mech,i}}{\varepsilon_{no\ creep,i}}$$

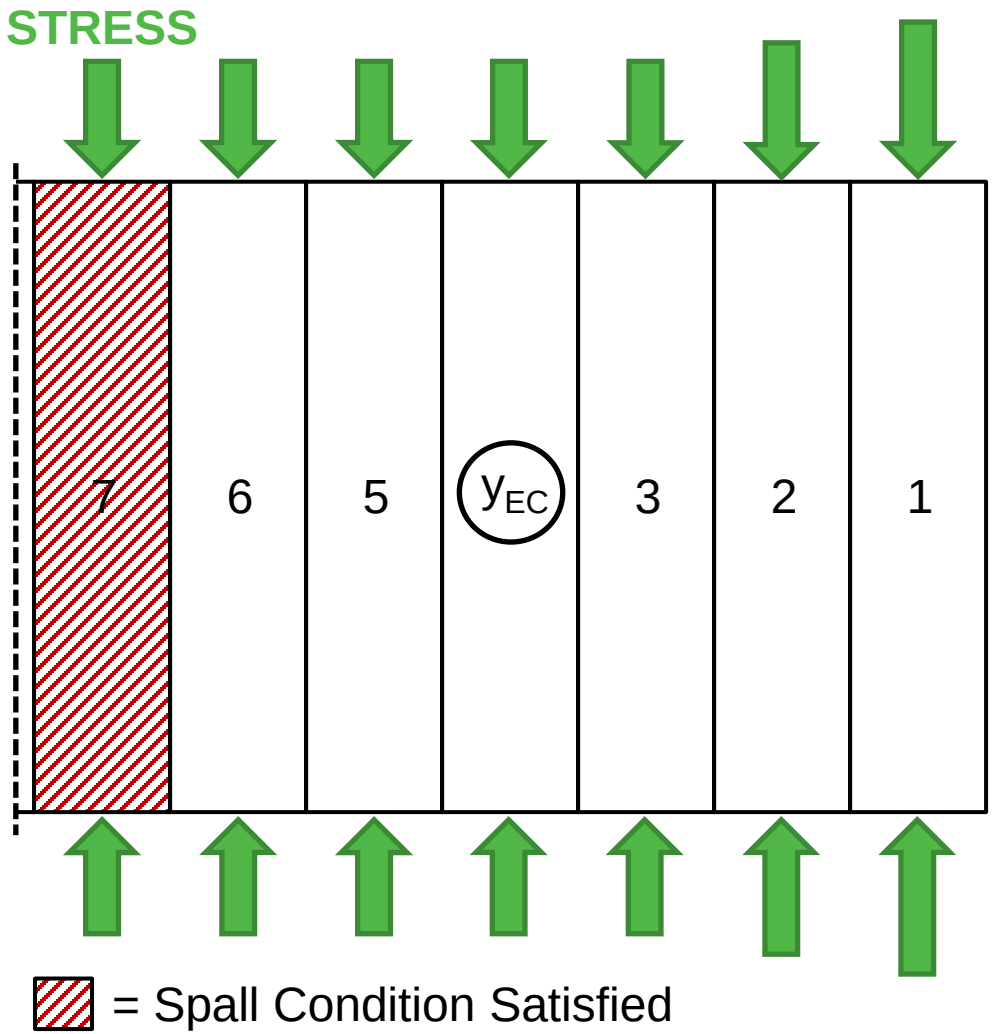


Analytical Prediction Methodology

Stability Check

Center of Stiffness

$$y_{EC} = \frac{\sum_1^n E_{secant,n}\, y_n\, A_n}{\sum_1^n y_n A_n}$$



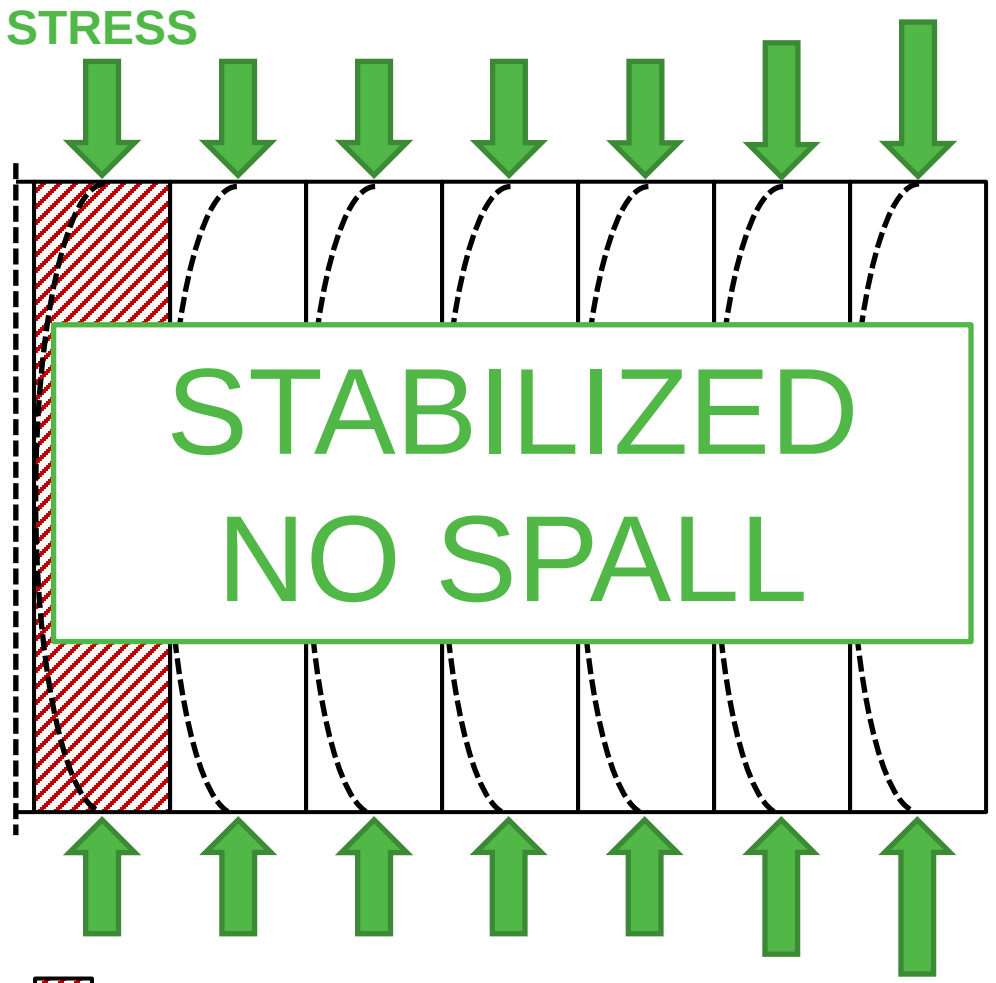
$$M_T = \sum_1^i \sigma_{mech,i} A_i (y_i - y_{EC})$$

$$P_T = \frac{\sum_1^n \frac{\sigma_{mech,n}}{f_{cT,n}}}{n} \times 100\%$$

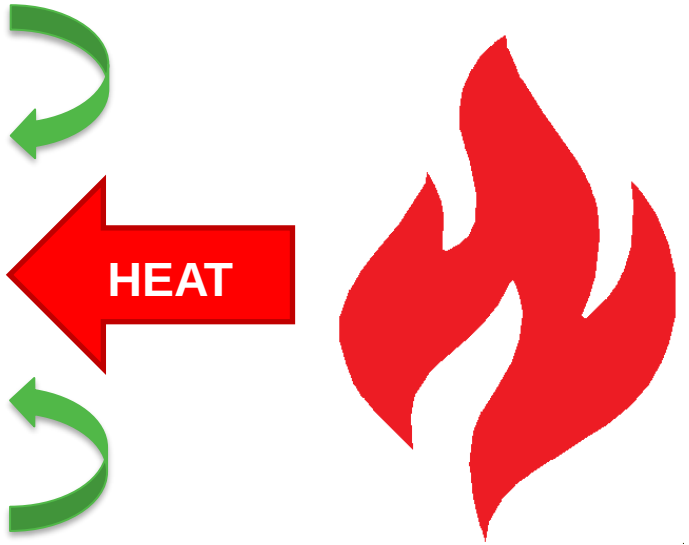
Analytical Prediction Methodology

Zhukov/Lu equation indicates a Spall Condition tensile failure

Mechanics evaluation indicates a **stabilizing moment** around the center of stiffness of the spalled layers. In effect the moment is bending the spalled layers such that they are in bearing on the rest of the cross-section.



$$M_T = \sum_{1}^{i} \sigma_{mech,i} A_i (y_i - y_{EC})$$



-OR-

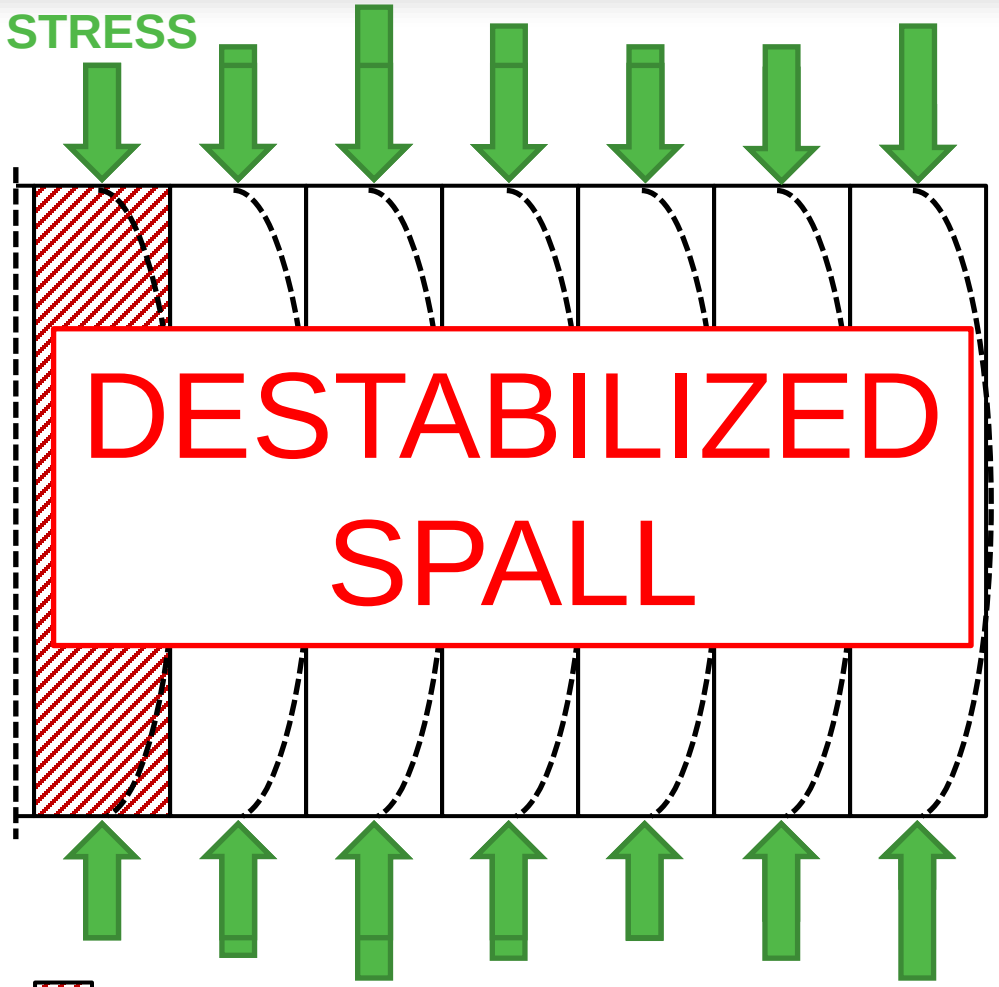
$$10\% \geq \frac{\sum_{i=1}^{n} \frac{\sigma_i}{f_{comp,T,i}}}{n} 100\%$$

= Spall Condition Satisfied

Analytical Prediction Methodology

Zhukov/Lu equation indicates a Spall Condition tensile failure

Mechanics evaluation indicates a **destabilizing moment** around the center of stiffness of the spalled layers. In effect the moment is bending the spalled layers outward toward the heat source. Suggestive of a compression failure as evident by the explosive nature of the spalling.



$$M_T = \sum_{1}^{i} \sigma_{mech,i} A_i (y_i - y_{EC})$$

-AND-

$$10\% \leq \frac{\sum_{i=1}^{n} \frac{\sigma_i}{f_{comp,T,i}}}{n} 100\%$$

Analytical Prediction Methodology

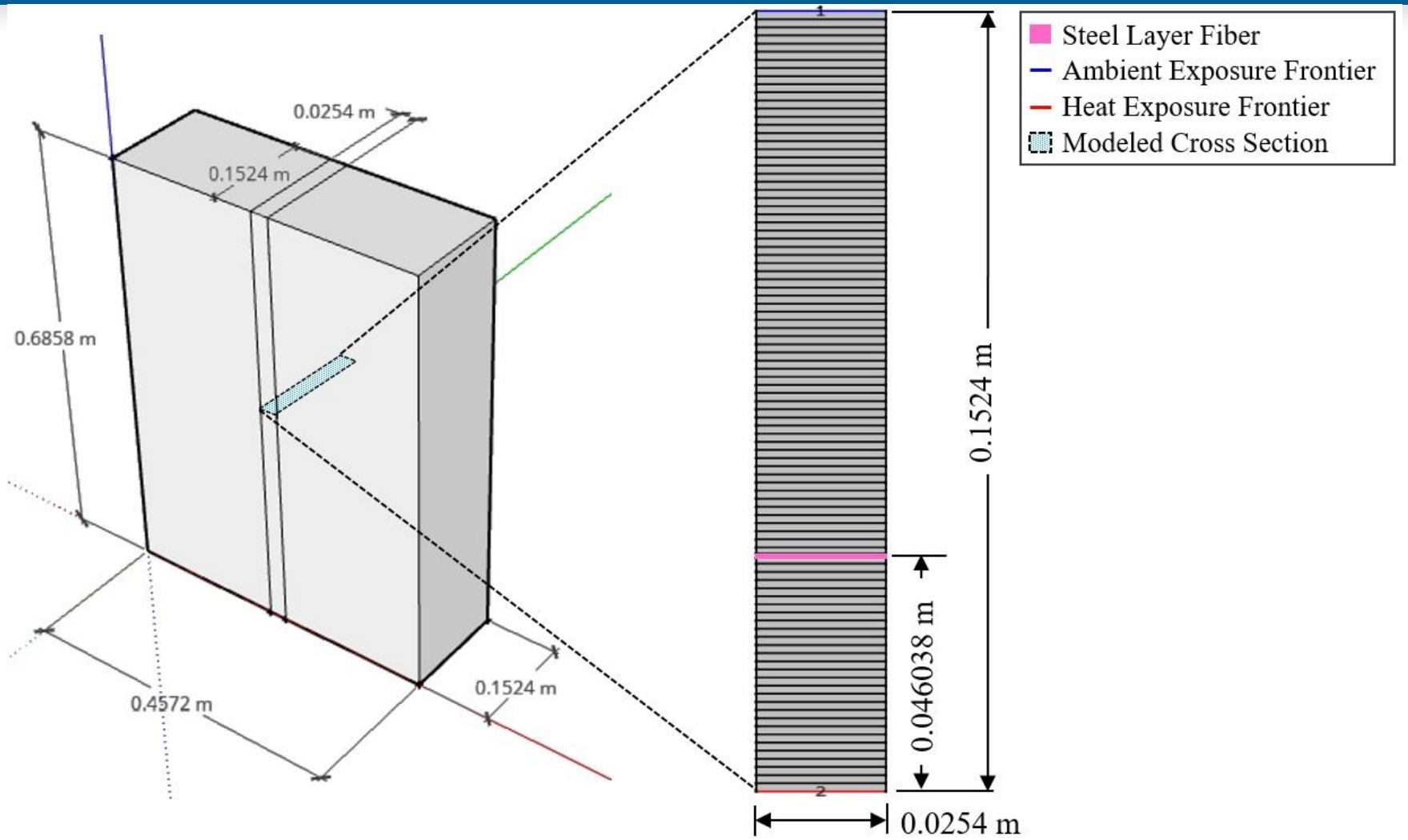
Example Validation Case: Specimen B-3.4-13.3-F3-M

- 39.7 ± 0.3 MPa compressive strength
- 4.6 ± 0.4 MPa splitting tension strength
- 37.0 ± 3.8 GPa elastic modulus
- 2372 kg/m3 oven-dried bulk density per ASTM C642-13 [45]
- 2.94 W/m-K thermal conductivity via Hot Disk per ISO 22007-2 [46]
- 1.47 mm2/s thermal diffusivity via Hot Disk per ISO 22007-2 [46]
- 2.05 MJ/m3-K volumetric heat capacity
- Axial Load: 14.34% of the nominal compressive strength

Spalling Occurred: in 228 seconds at 10 mm of depth

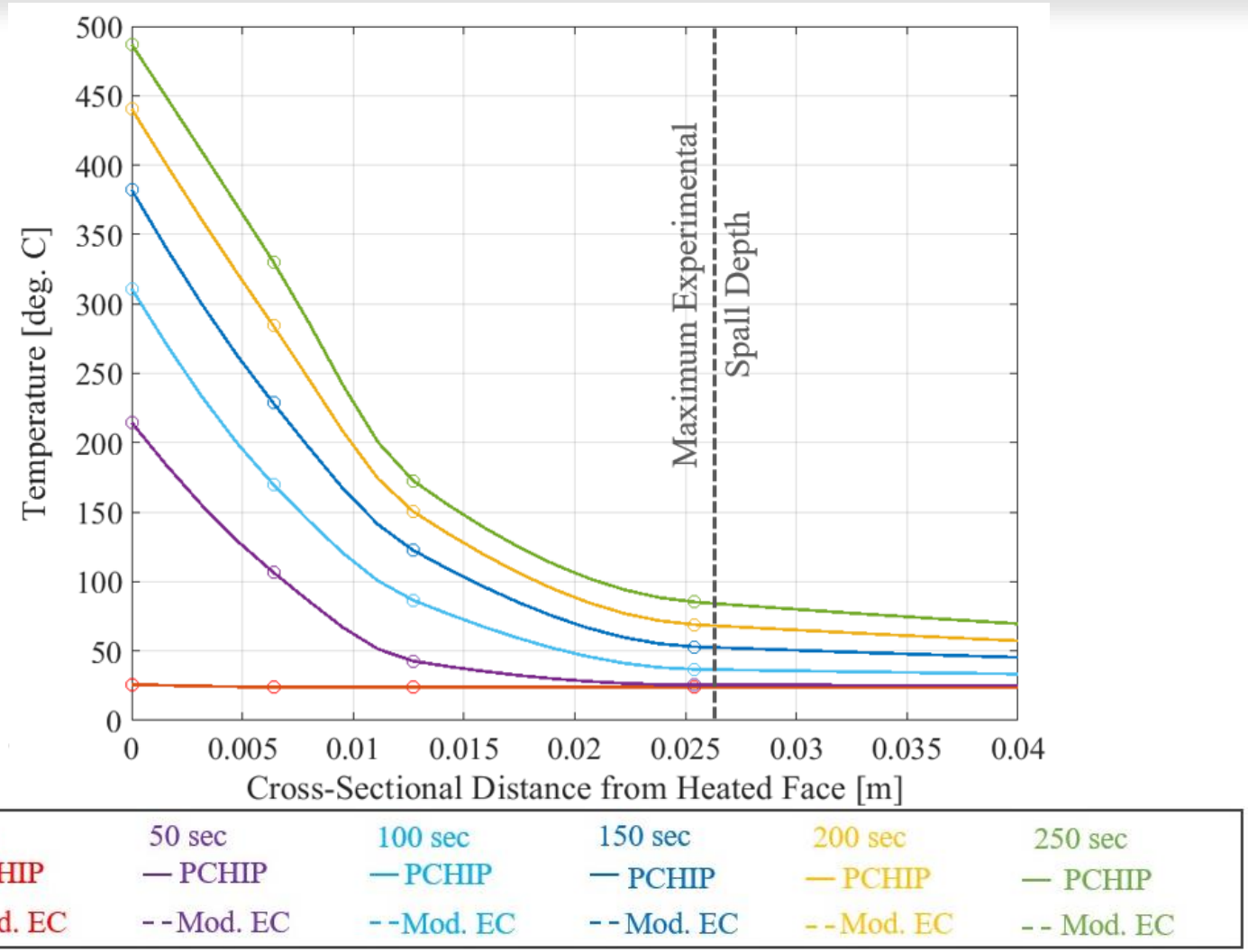
Analytical Prediction: Validation Example

STRUCTURAL CONDITION



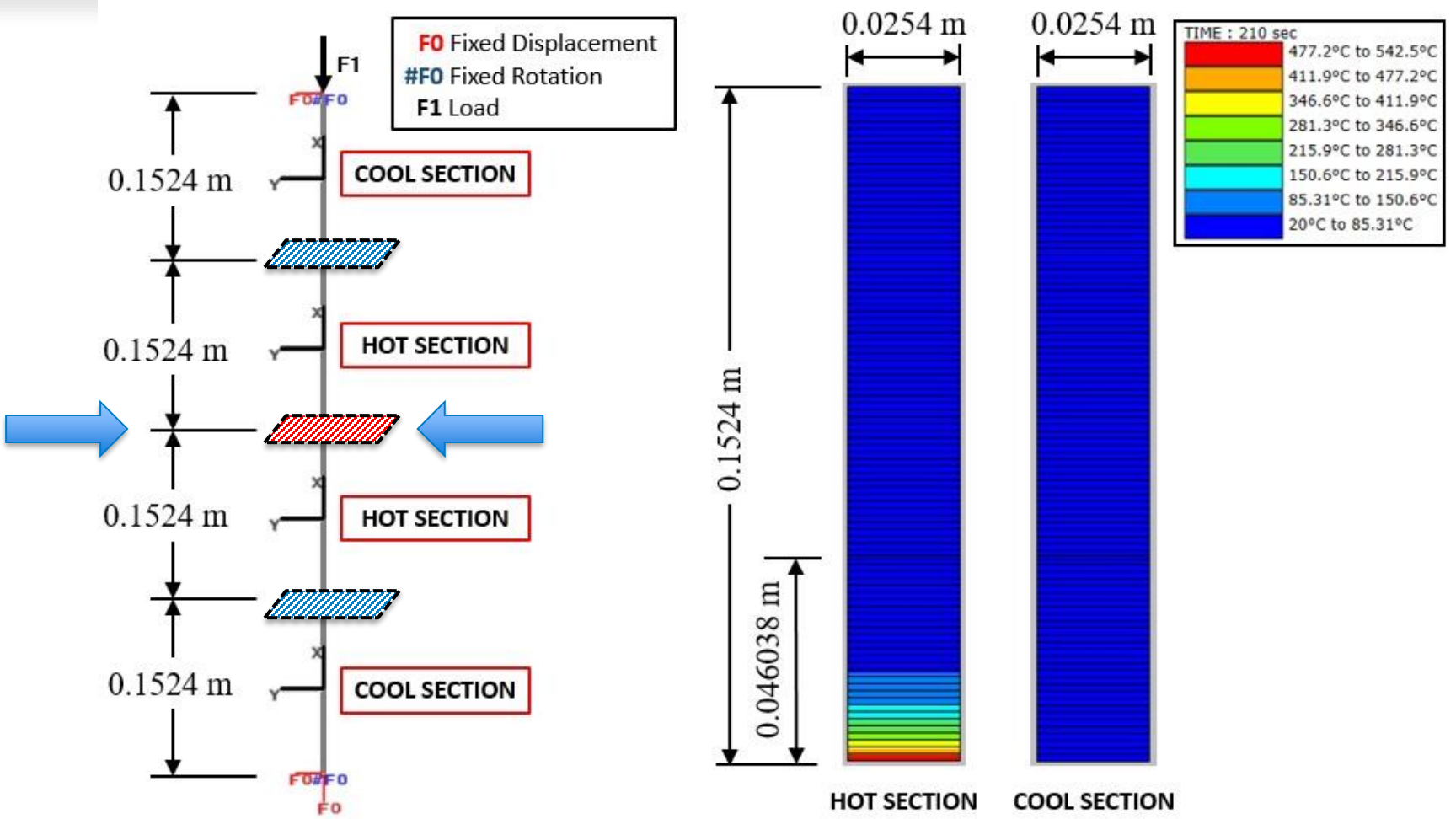
Analytical Prediction: Validation Example

TEMPERATURE ANALYSIS



Analytical Prediction: Validation Example

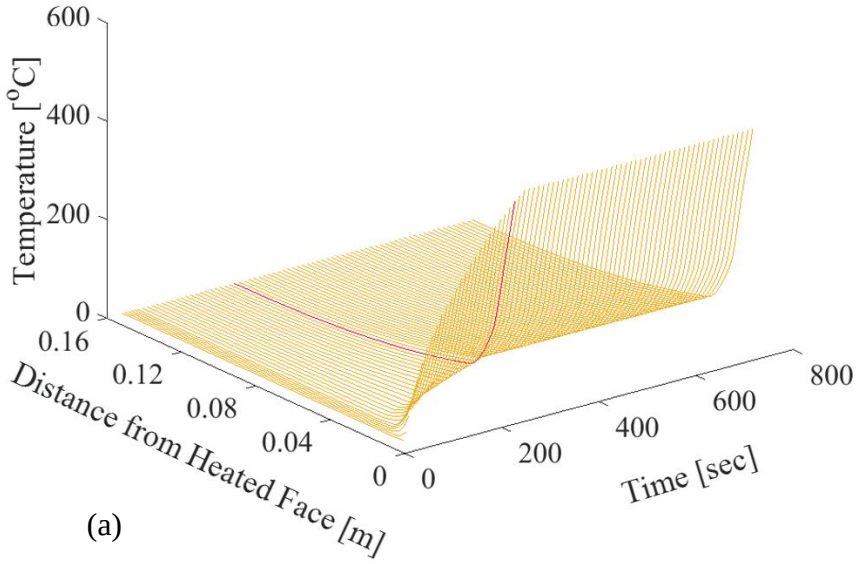
MECHANICAL ANALYSIS



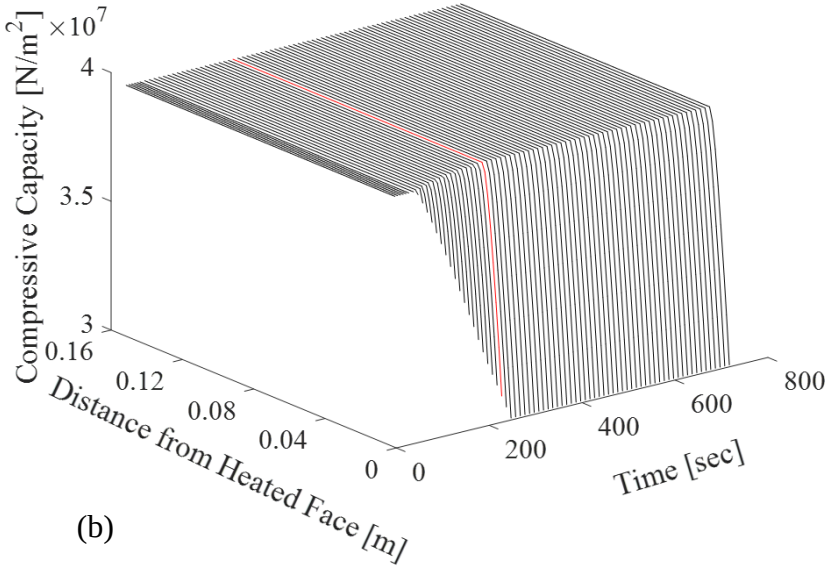
MECHANICAL MODEL

TEMPERATURE HISTORY INPUT

SPALL PREDICTION ANALYSIS



(a)



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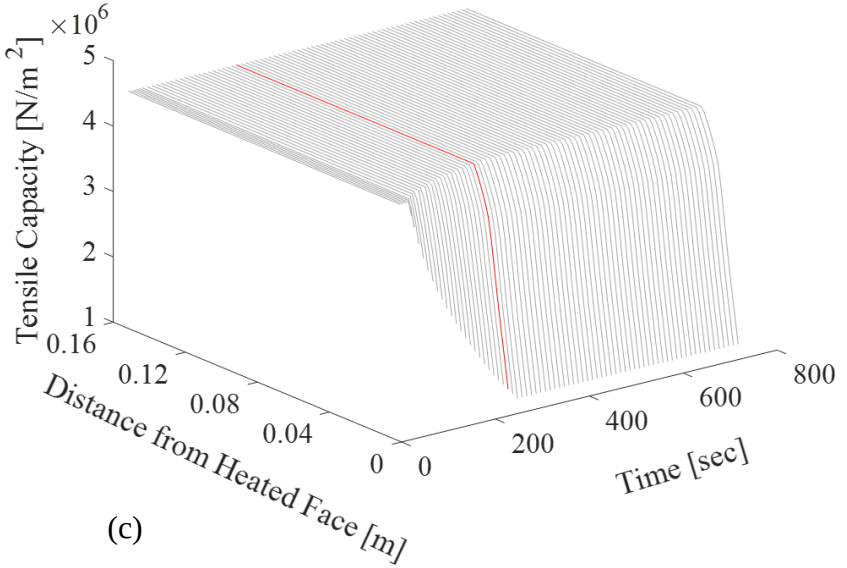

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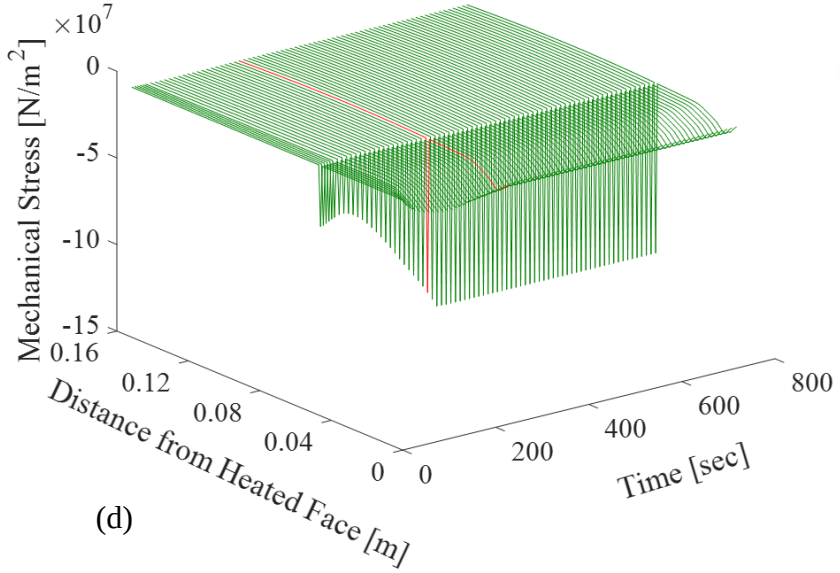

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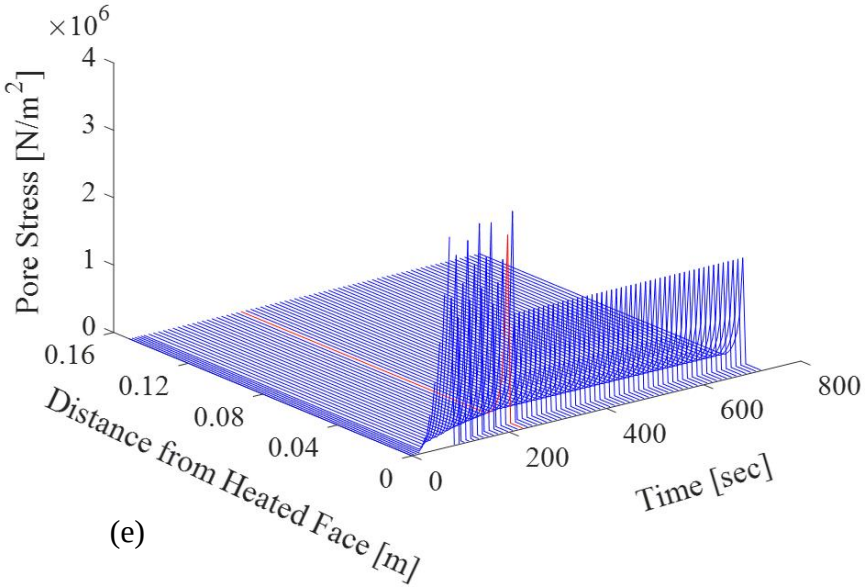

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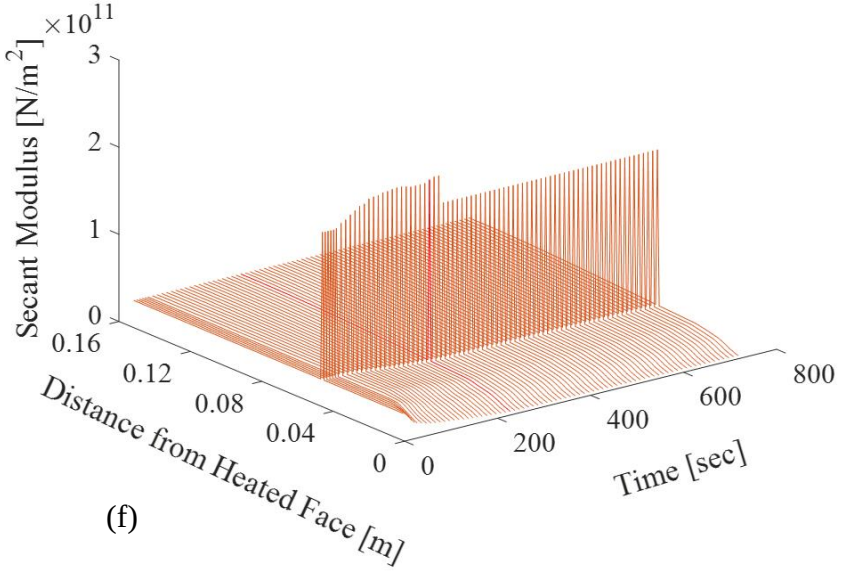

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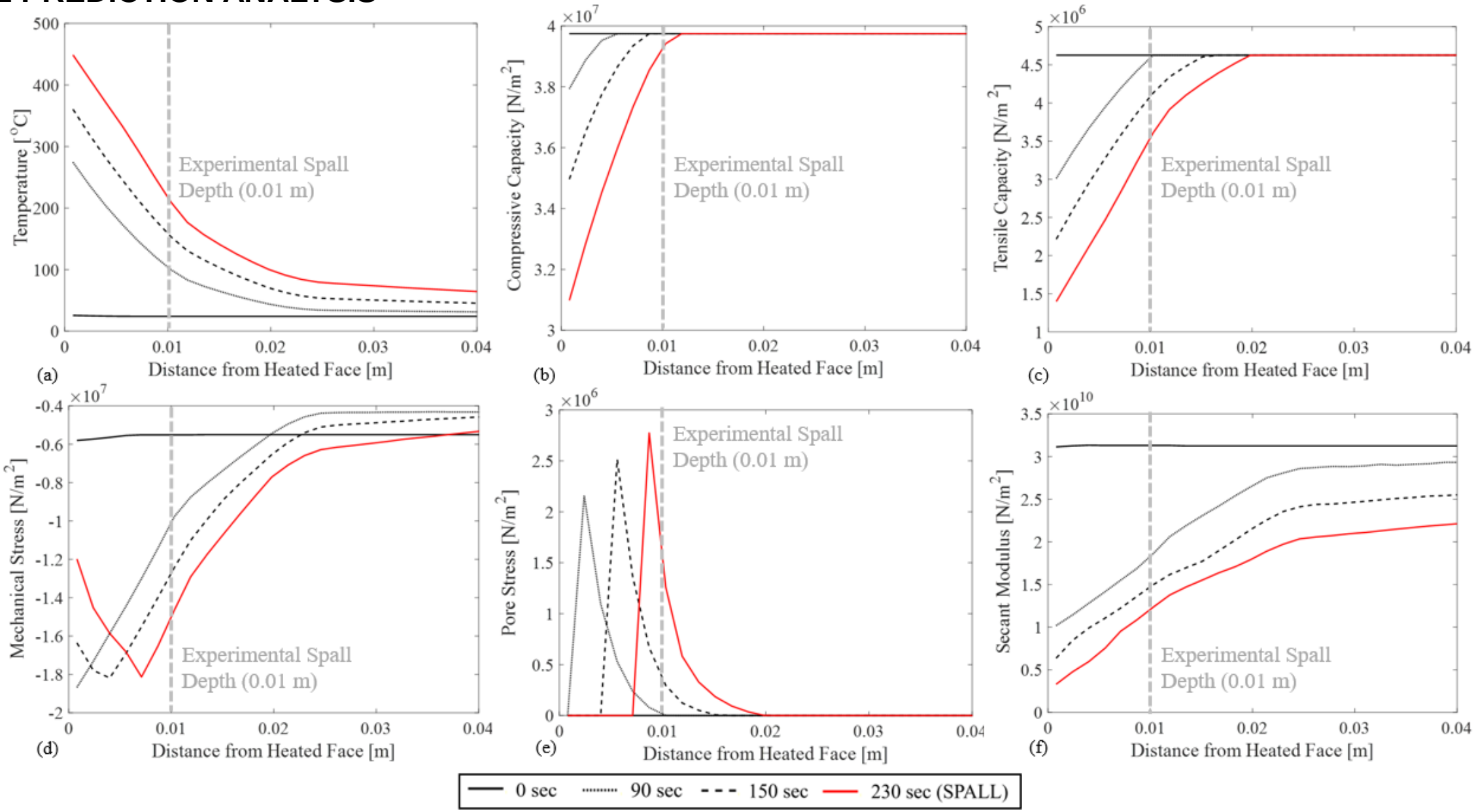
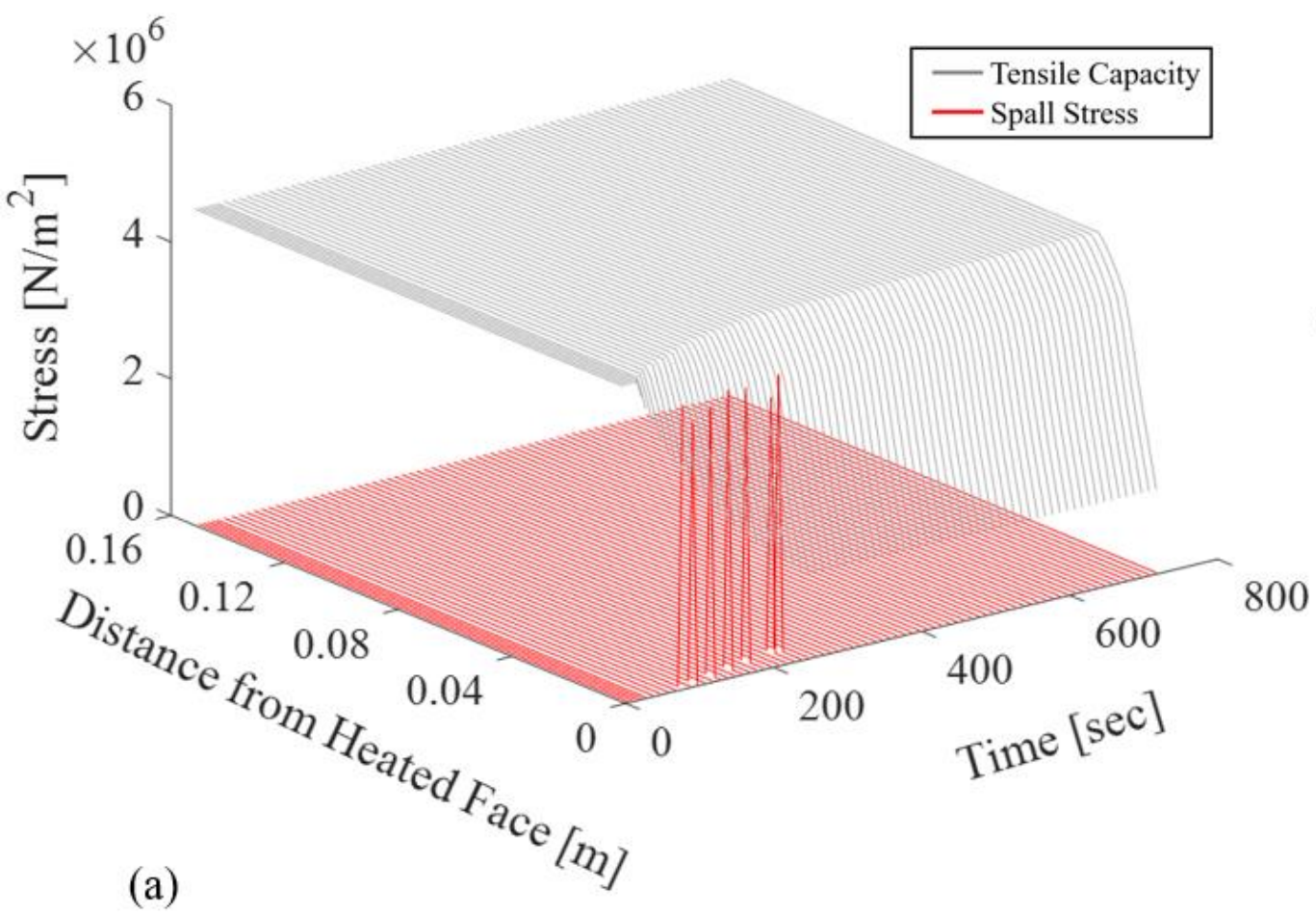
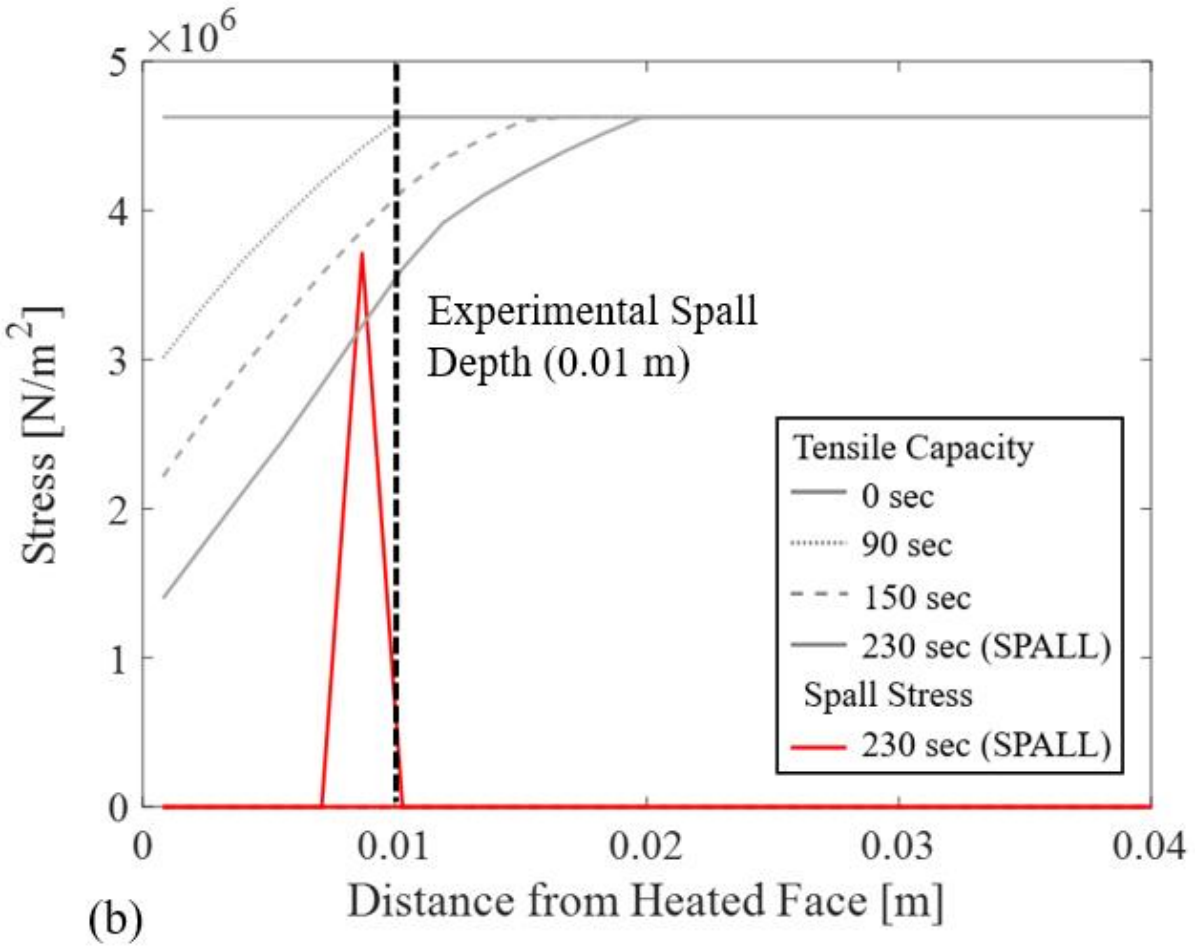
SPALL PREDICTION ANALYSIS



Analytical Prediction: Validation Example





Analytical Prediction: Validation Example

Destabilization Requirements Cracked Section

$Spall\ Depth > 7.9\ mm$ $Avgerage\ Stress\ to\ Capacity \geq 10\%$ $Induced\ Moment < 0$

Table 3 - Spall Prediction Output Summary for Specimen B-3.4-13.3-F3-M

Model Time [sec]	Exp. Time [sec]	Surface Fiber Temp. [°C]	Spall Depth [mm]	Spalled Fiber Temp. [°C]	Cracked Section CG [mm]	Cracked Section Stress Center [mm]	Cracked Section Stiffness Center [mm]	Cracked Section Avg. Stress to Cap. [%]	Cracked Section Induced Moment [N-mm]	Spall Occurrence
110	80	257.8	1.6	257.8	0.80	0.80	0.80	13.9	0.0	NO
130	100	290.4	3.2	251.3	1.60	1.57	1.65	13.9	115.0	NO
160	130	334.2	4.8	254.3	2.40	2.40	2.29	13.9	-235.2	NO
190	160	373.1	6.4	257.9	3.20	3.26	3.09	13.9	-470.5	NO
220	190	409.2	7.9	256.8	3.98	4.12	3.95	13.9	-559.2	NO
260	**230**	**448.9**	**9.5**	**251.3**	**4.77**	**5.06**	**4.91**	**14.1**	**-551.7**	**YES**
270	240	458.3	9.5	258.0	4.77	5.11	4.93	15.4	-662.5	YES

Analytical Prediction: Validation Example

Label	Spall	Load per nominal f'c	Experimental			Prediction					
						Experimental Temperature					
			Spall Time	Spall Depth	Surface Temp. at Spall	Spall Time	Spall Depth	Time Error	Depth Error	Surface Temp.	Spall Depth Temp
		[%]	[sec]	[mm]	[°C]	[sec]	[mm]	[sec]	[mm]	[°C]	[°C]
B-3.4-13.3-F3	Y	14	228	10	448.9	230	9.5	2	-0.5	448.9	251.3
B-3.3-13.3-F3	Y	16	204	11	382.0	200	9.5	-4	-1.5	382.0	255.7
B-2.9-13.6-F3	N	3	NA	NA	NA	NO SPALL		NA	NA	NA	NA
B-2.5-07.1-F3	N	1	NA	NA	NA	NO SPALL		NA	NA	NA	NA
B-0.0-00.7-F3	N	14	NA	NA	NA	NO SPALL		NA	NA	NA	NA
B-2.9-06.4-F4	Y	14	384	15	440.8	270	9.5	-114	-5.5	360.7	250.8
B-2.4-06.2-F4	N	15	NA	NA	NA	NO SPALL		NA	NA	NA	NA

Acknowledgements

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Questions?

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Experimentation: Heat Flux Application