Integration of Non-contact Ultrasonic and Computer Vision for Setting time and Sawcut Timing

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- Provisional patent has been applied based on the research presenting. Algorithm and technology discussed in the presentation cannot be used without consents of the authors.

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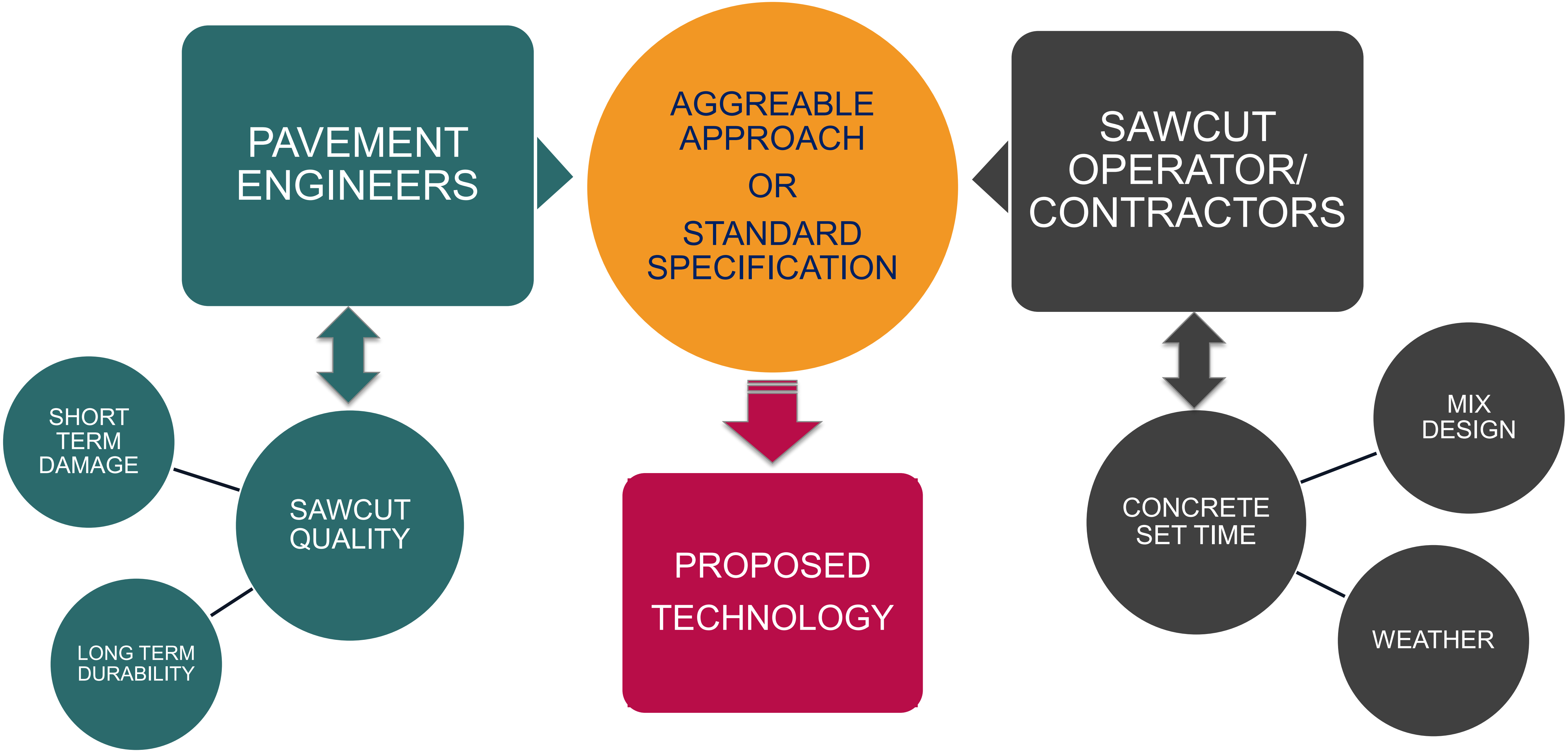
Motivation


PAVEMENT ENGINEERS
AGGREABLE APPROACH
OR
STANDARD SPECIFICATION
SAWCUT OPERATOR/ CONTRACTORS
SHORT TERM DAMAGE
SAWCUT QUALITY
LONG TERM DURABILITY
PROPOSED
TECHNOLOGY
MIX DESIGN
CONCRETE SET TIME
WEATHER

Importance of Sawcut Timing and Damage

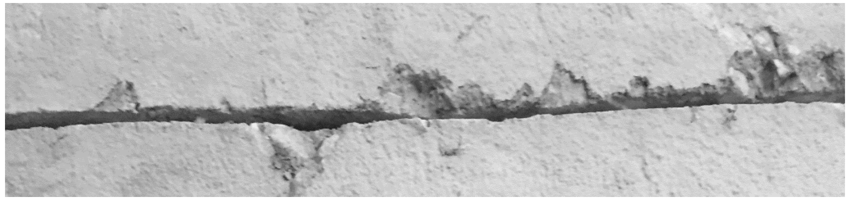
Common pavement engineering question: **When to saw-cut concrete? What is a good sawcut?**

Transverse cracks

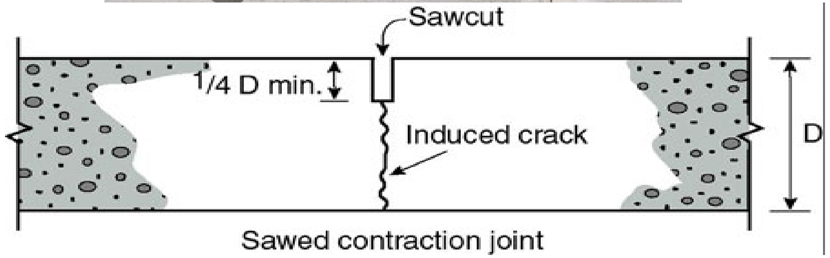
Too late

ASK

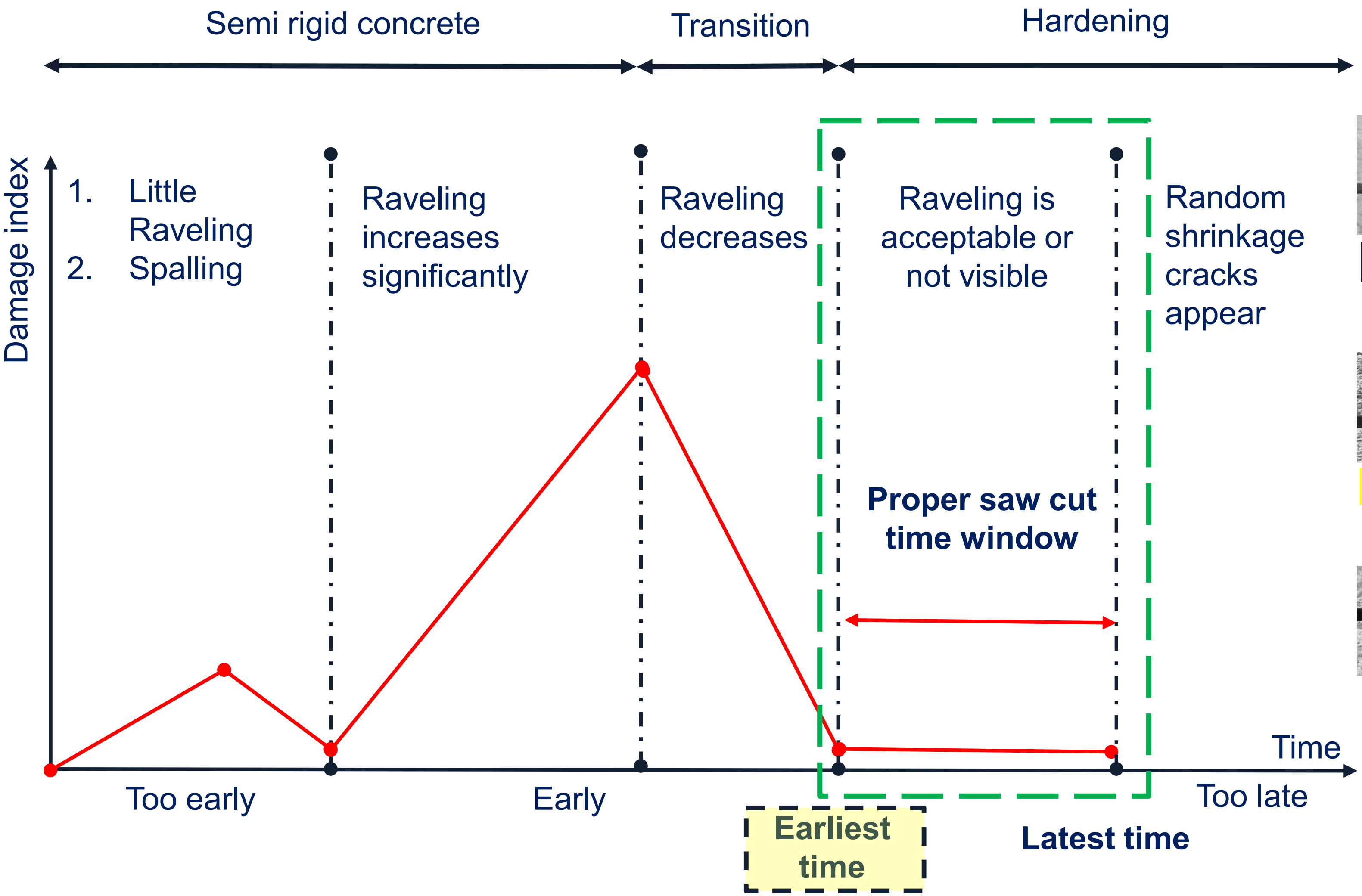
Too early

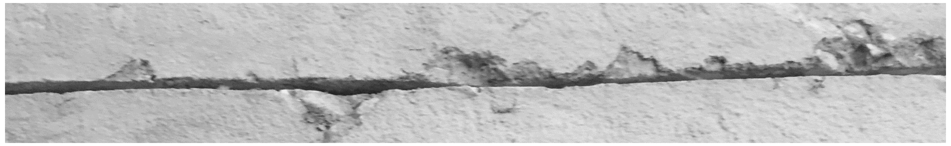


Raveling

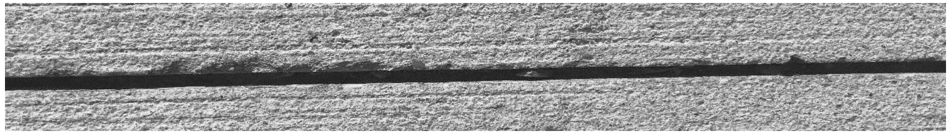


Development of Raveling with Time

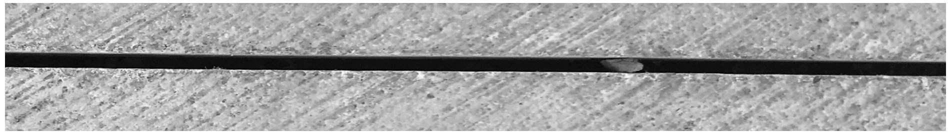




Unacceptable raveling – sawed too early



Moderate raveling – sawed early or on time



No raveling – late sawcut

Goal: Determine Earliest time of saw cutting

Determination of Sawcut Timing

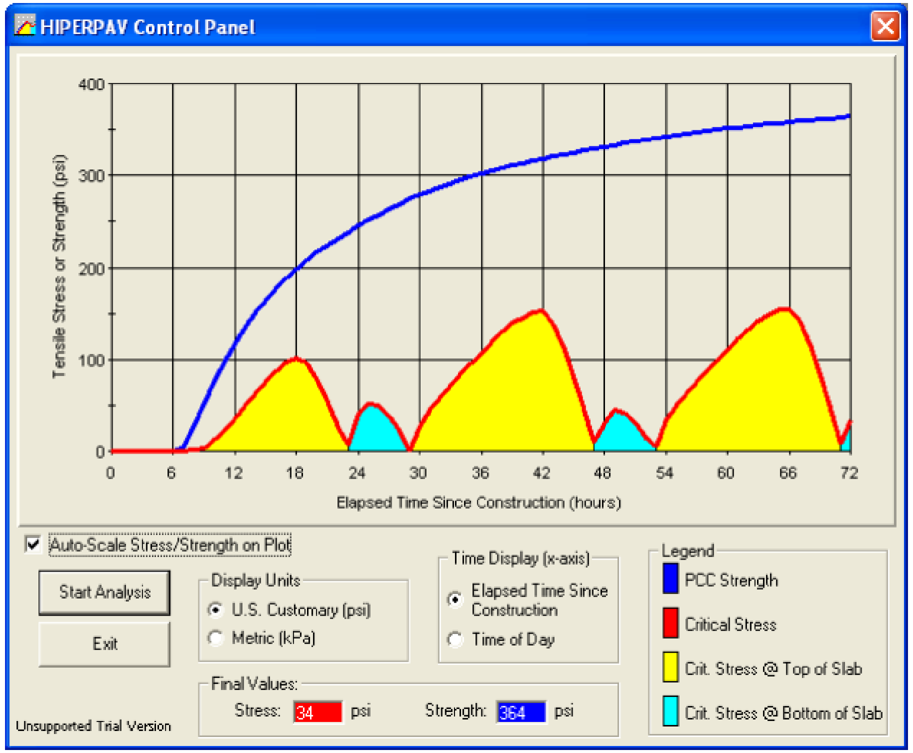
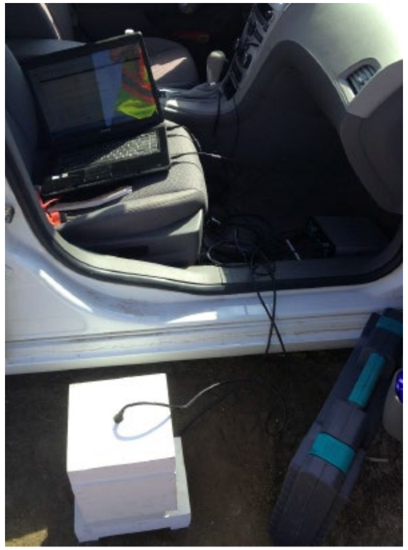


Figure 2.11: Hiperpav analysis showing the elapsed time since construction (x-axis) versus the tensile strength or stress development in the slab (y-axis)

Determine the timing of saw cutting based on the concrete strength and stress is modeled using HIPERPAVE software
(Raoufi et al. 2009)



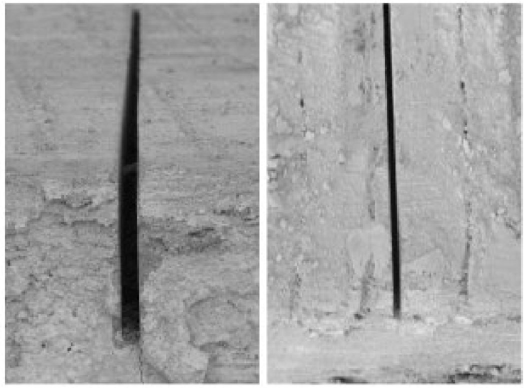
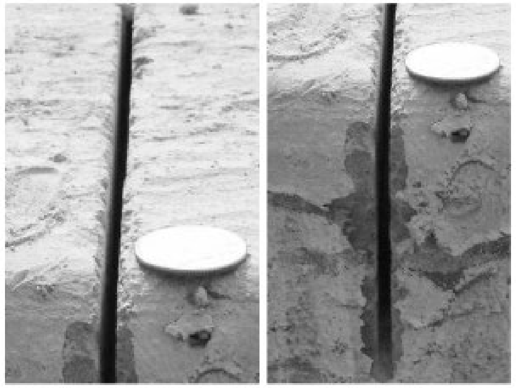
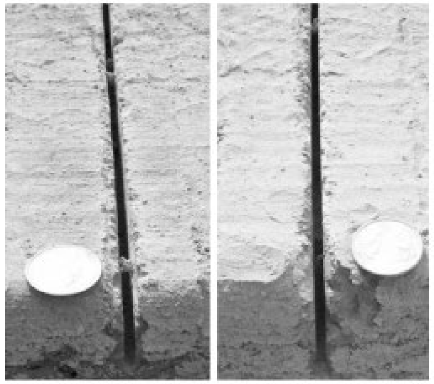
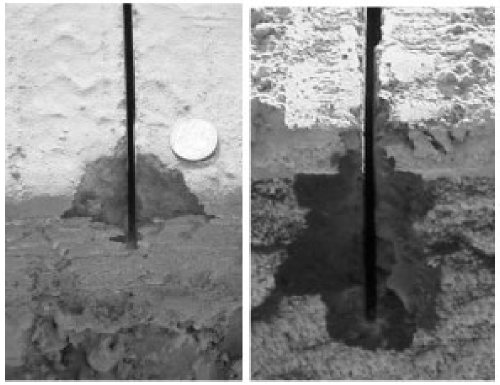
(Taylor & Wang, 2014)

Sample research:

1. Taylor & Wang, 2014
2. Krstulovich et al. (2011)
3. Smith (2007)
4. Weiss et al. (2009)
5. Lange et al. (2007)
6. Zollinger et al. (2005)
7. Okamoto (1994)
8. Michael et al. (1985)

Limitations:
1. Access
2. Contact
3. Companion specimens

Quantification of Sawcut Damage Extent

JRI	Description	Example
0	No raveling or edge damage observed. No breakout at slab edge	
1	Rougher edge observed. Breakout at slab edge primarily characterized by loss of curing compound film, not concrete.	
2	Moderate raveling or edge damage (e.g., displaced aggregate, spalling) observed along less than 50% of joint.	
3	Extensive raveling or edge damage or both observed along greater than 50% of joint.[a]	

(Krstulovich Jr, Van Dam, Smith, & Gawedzinski, 2011)

Limitations:

1. Relative quantification

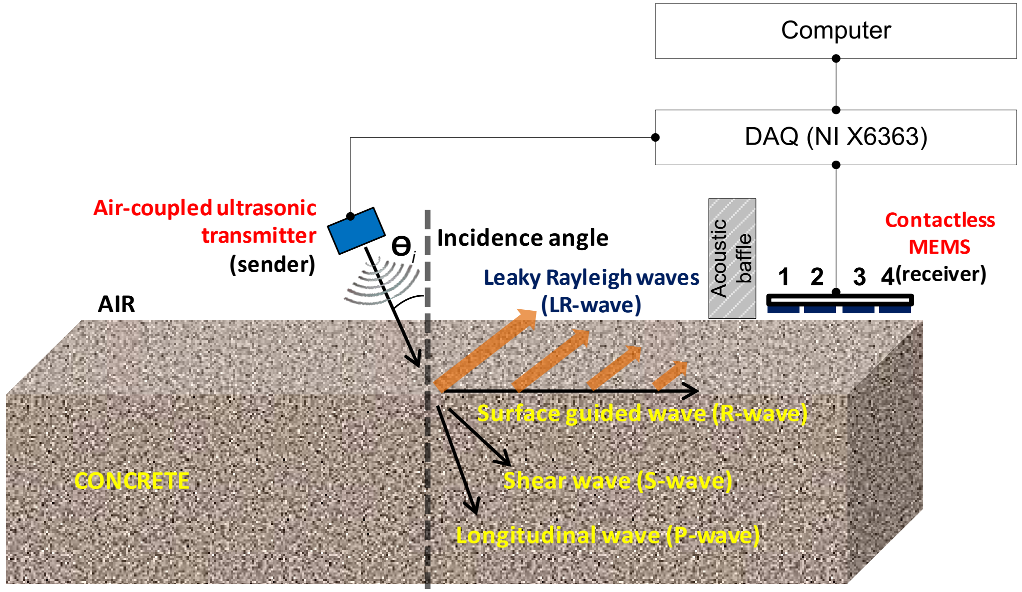
Research Objective

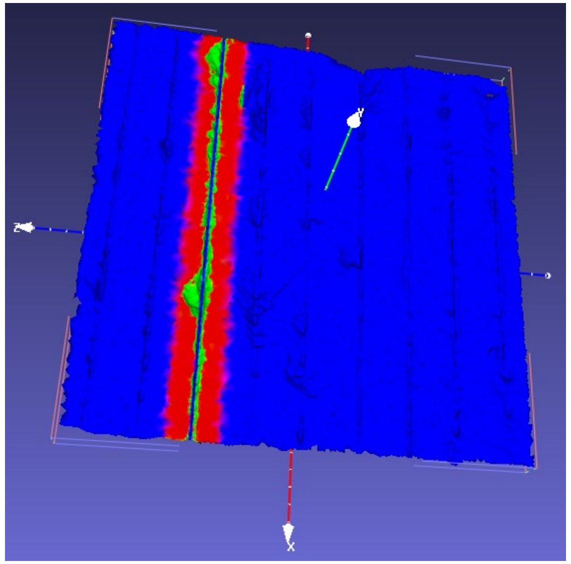
Limitations: Access, contact, & companion specimens

Limitations: Relative quantification

Technique 1:
Non-contact Ultrasonic Testing System (UTS)

Technique 2:
Computer vision-based technique





In-situ final setting time

Quantify sawcut damage

Objective

Estimate earliest time of saw cutting when the risk of raveling is minimal

Laboratory Test Setup Design and Specimens

Concrete Mix design

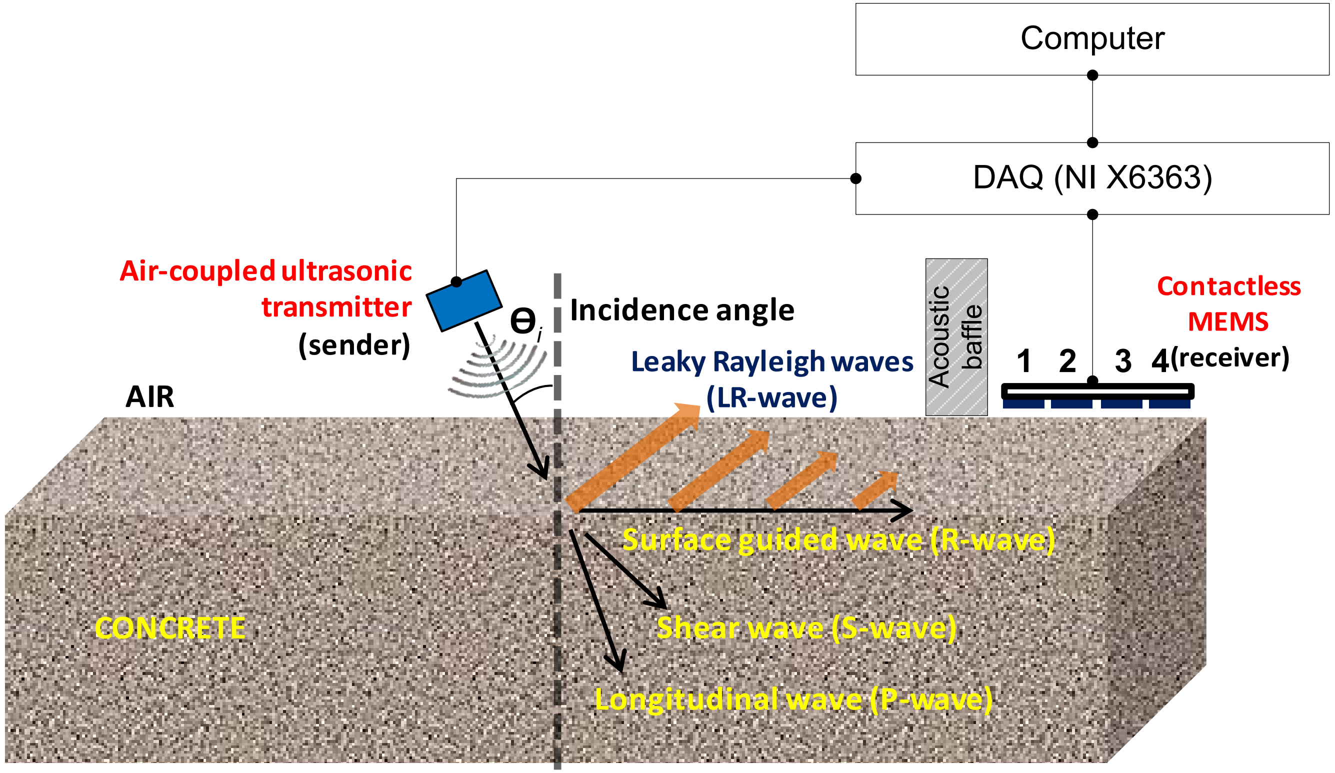
Mix ID	w/cm ratio	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Cement (kg/m^3)	Fly ash (kg/m^3)	Water (kg/m^3)
C-39	0.39	1124	673	336	-	131
C-45	0.45	1124	673	336	-	151
C-50	0.5	1124	673	336	-	168
C-FA-39	0.39	1124	673	303	33	131
C-FA-45	0.45	1124	673	303	33	151
C-FA-50	0.5	1124	673	303	33	168

Portland cement: C-39, C-45, C-50

Cement-Fly ash mixtures: C-FA-39, C-FA-45, C-FA-50

Technique 1:

Determine Final Setting Time
by
Non-contact Ultrasonic Testing System (UTS)



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Importance of Final Setting Time

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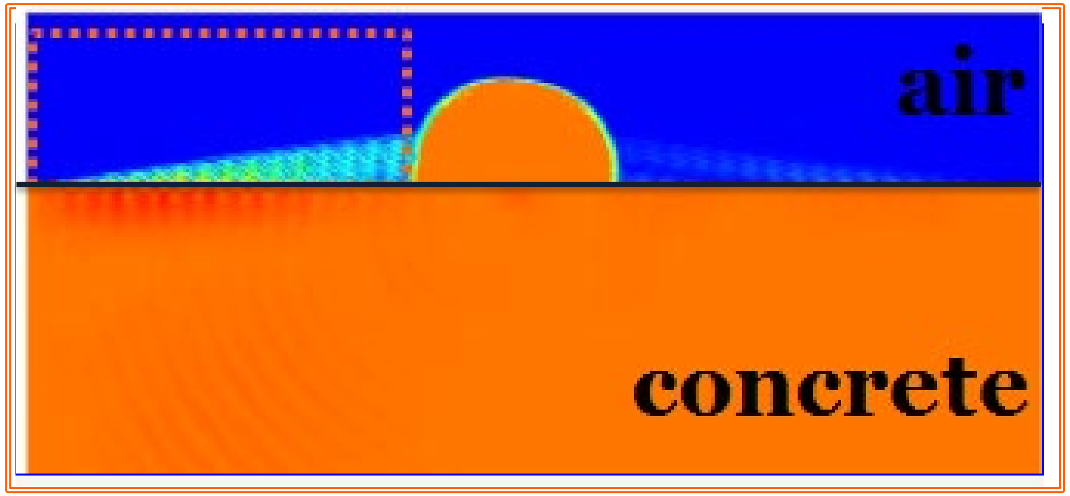
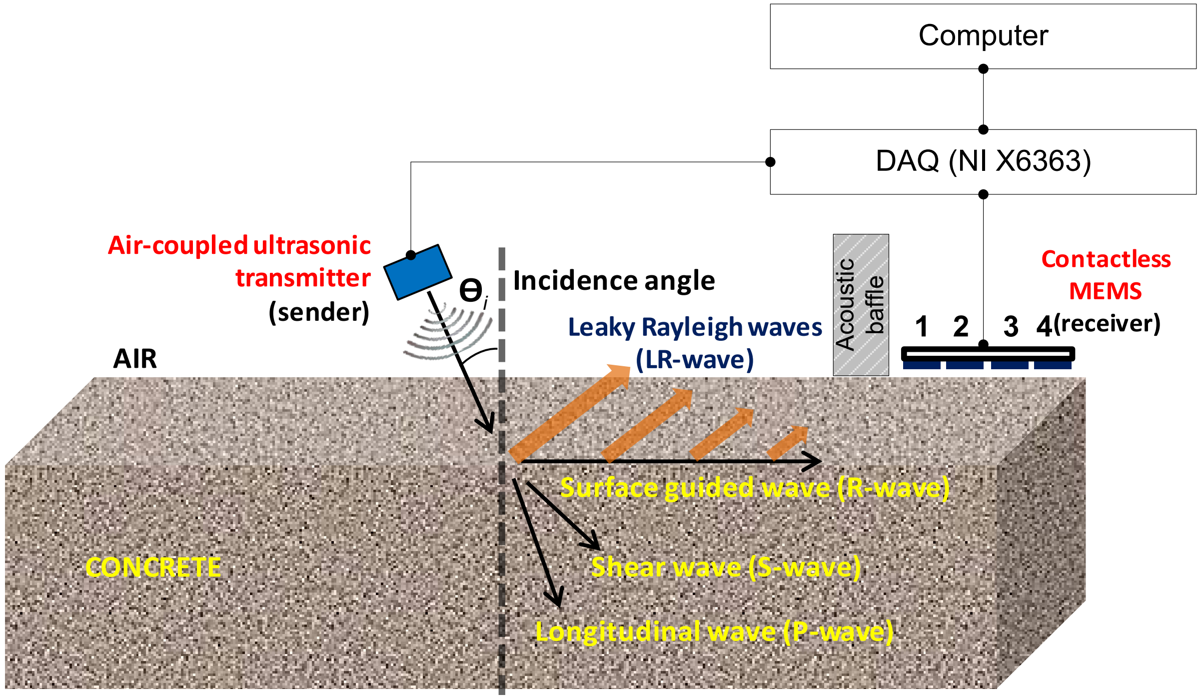
Final set time of concrete has a significant role for construction activities

Non-contact Ultrasonic Testing System (UTS)

LR wave



Leaky-Rayleigh wave propagation



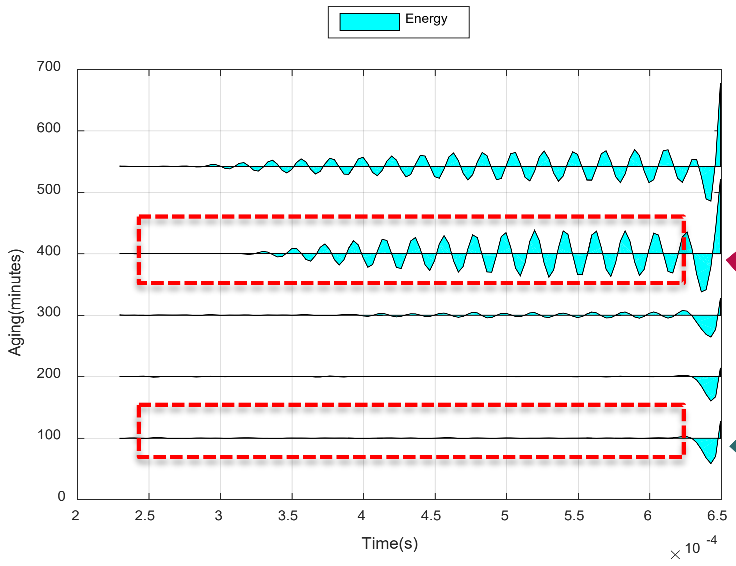
Generalized Rayleigh-wave equation:

$$4\left(\frac{C_S}{C}\right)^2\left[1-\left(\frac{C_S}{C}\right)^2\right]^{1/2}\left[\left(\frac{C_S}{C_p}\right)^2-\left(\frac{C_S}{C}\right)^2\right]^{1/2}+\left[1-2\left(\frac{C_S}{C}\right)^2\right]^2=-i\frac{\rho_l}{\rho_s}\left[\frac{\left(C_S/C\right)^2-\left(C_S/C_P\right)^2}{\left(C_S/C_P\right)^2-\left(C_S/C\right)^2}\right]$$

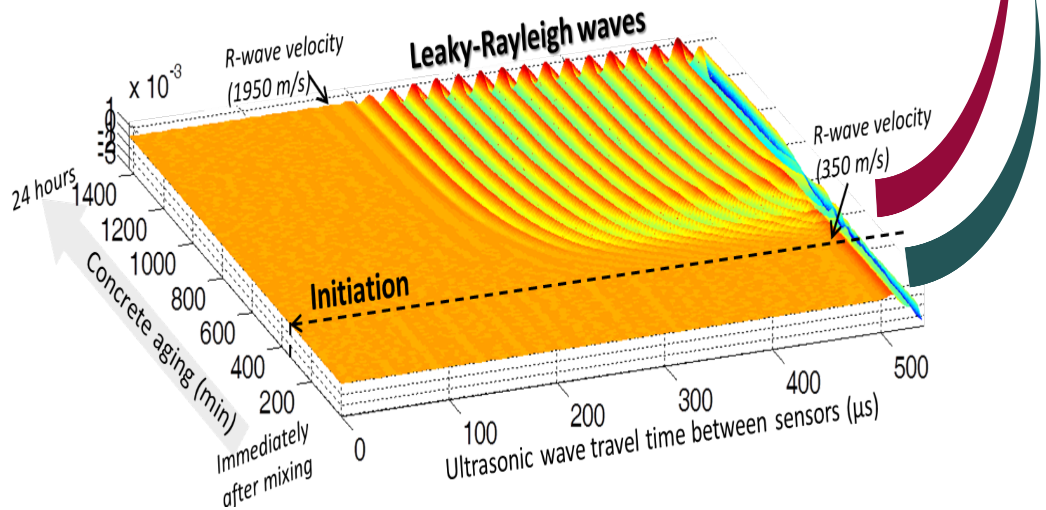
… (Zhu, Popovics et al. 2004)

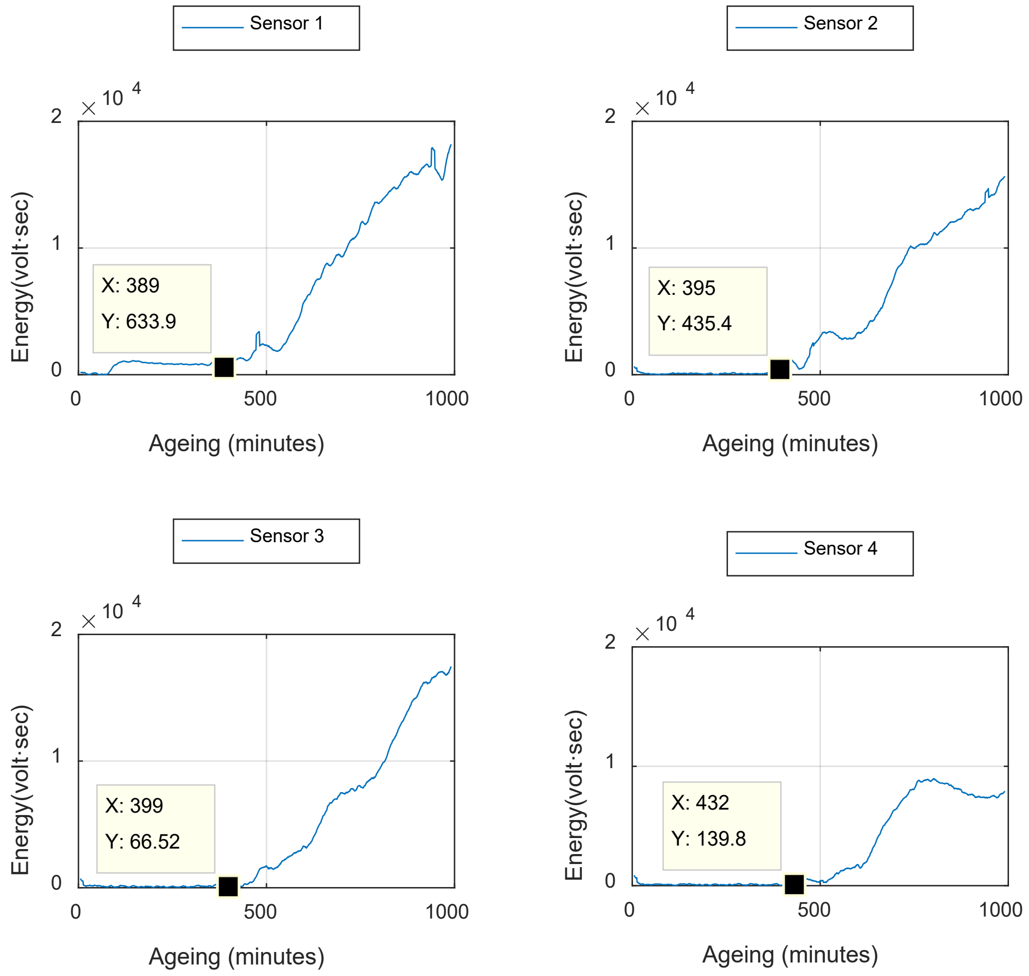
- C is velocity of the wave along the boundary.
- C_S is velocity of S-wave, C_P is velocity of P-wave, ρ_l and ρ_s are density of liquid and solid.
- Low density ρ_l, the equation has complex root C (known as slightly larger than velocity of R-wave).

Leaky Wave Energy over Time



Energy of LR-wave signals at different times





LR-wave energy over time for the four MEMS sensors (20 mm spacing)

UTS Final Setting Time (t_f) Results

1. t_f followed the expected trends with higher t_f for higher w/cm and fly ash addition

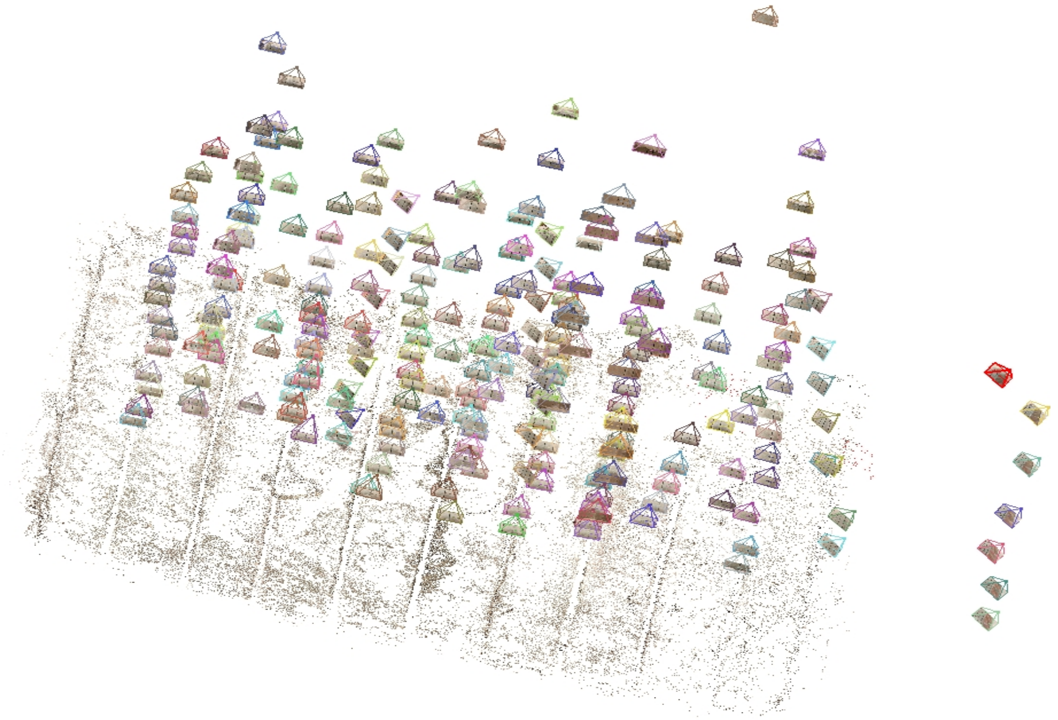
2. **High reliability** (standard deviation = 21 minutes and coefficient of variation = 8%)

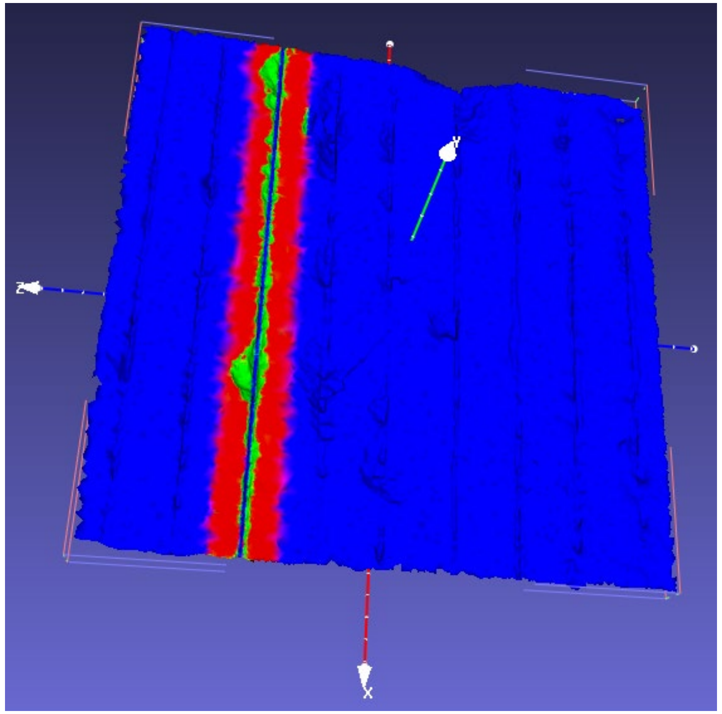
Concrete Mix ID	Average UTS final setting times, t_f (minutes)	Standard deviation (minutes)	Coefficient of variation (%)
C-39	276	21	8
C-45	331	13	4
C-50	404	19	5
C-FA-39	260	11	4
C-FA-45	396	6	1
C-FA-50	444	7	1

Technique 2:

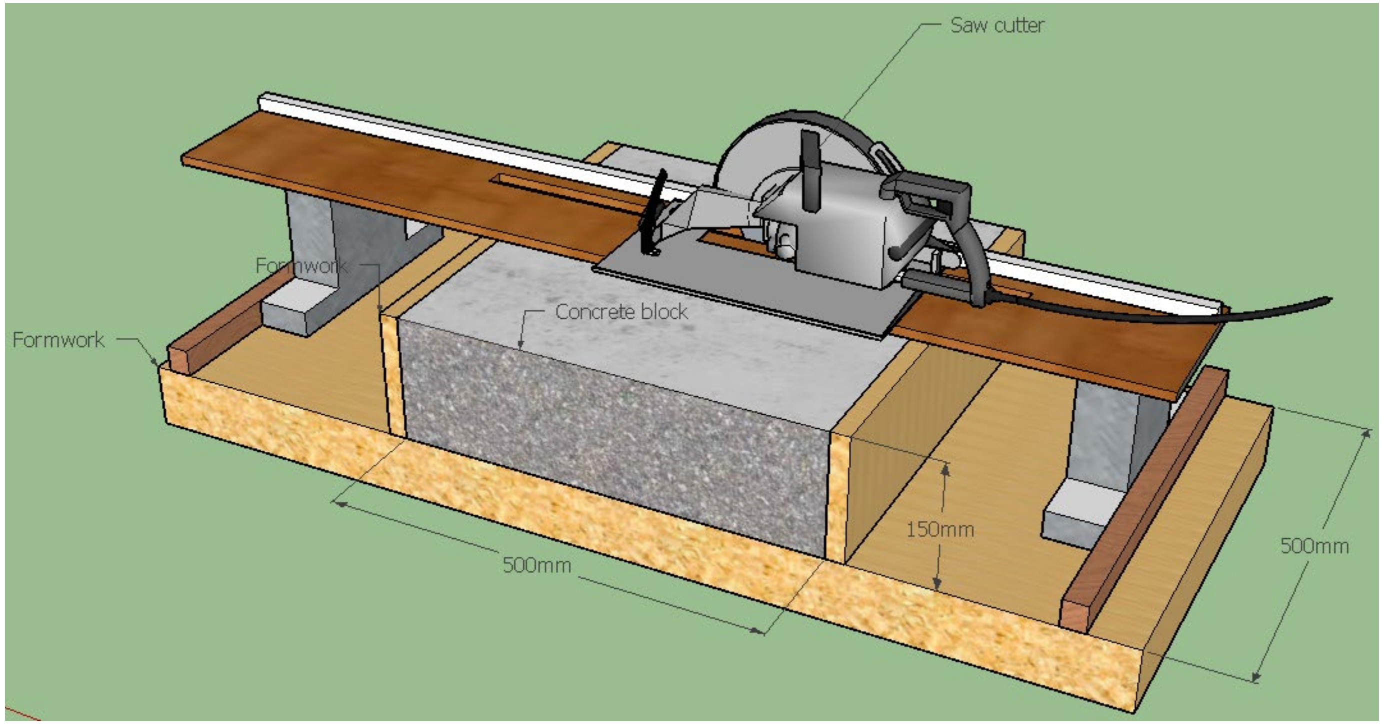
Quantify Raveling Damage:

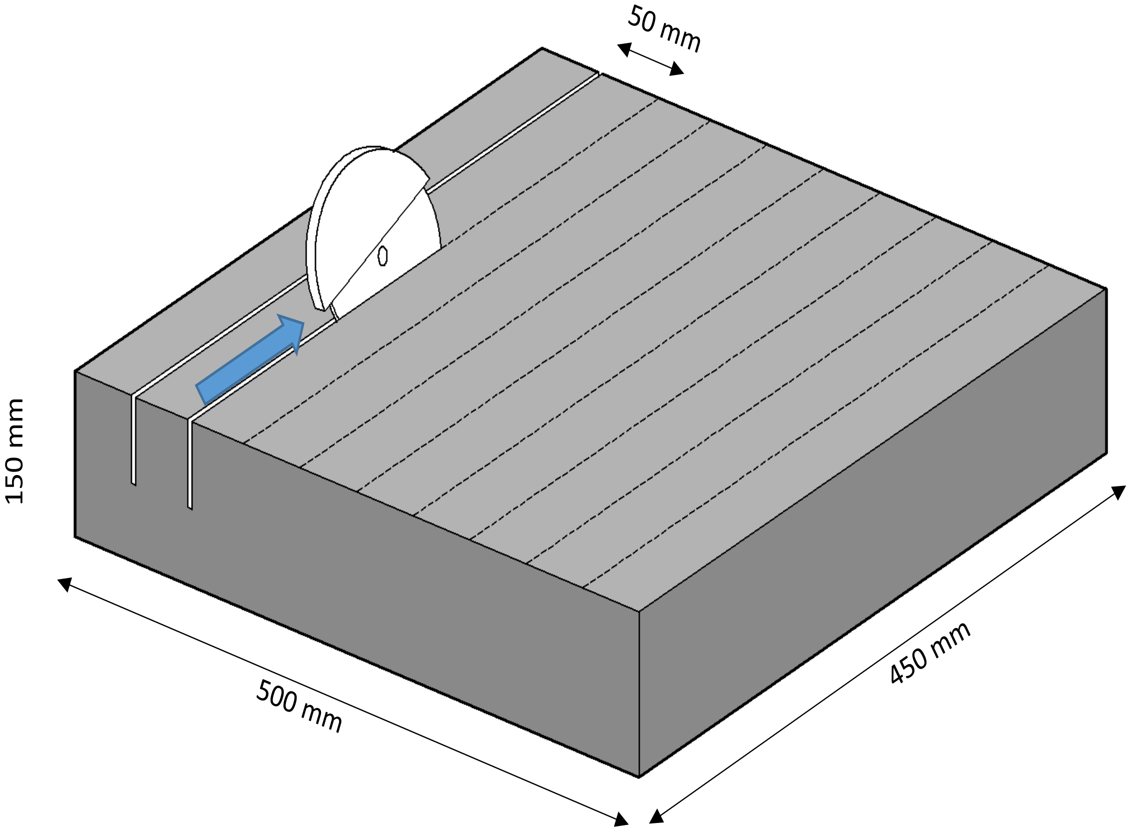
Computer Vision





Schematic of Test Slab





3D Point Cloud Reconstruction

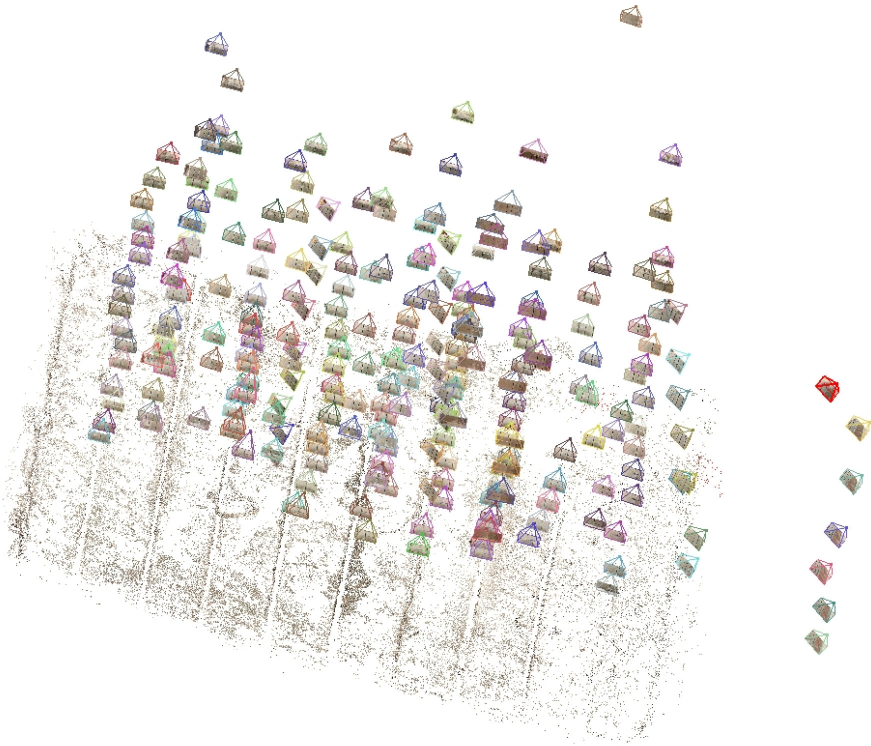
Step 1:

- Take multiple pictures of each saw cut
- Construct point cloud and dense model

Step 2:
Build Mesh model

Step 3:
Compute surface area of damaged and undamaged elements

Point cloud model



(Snavely et al. 2006)

Meshing 3D Point Cloud

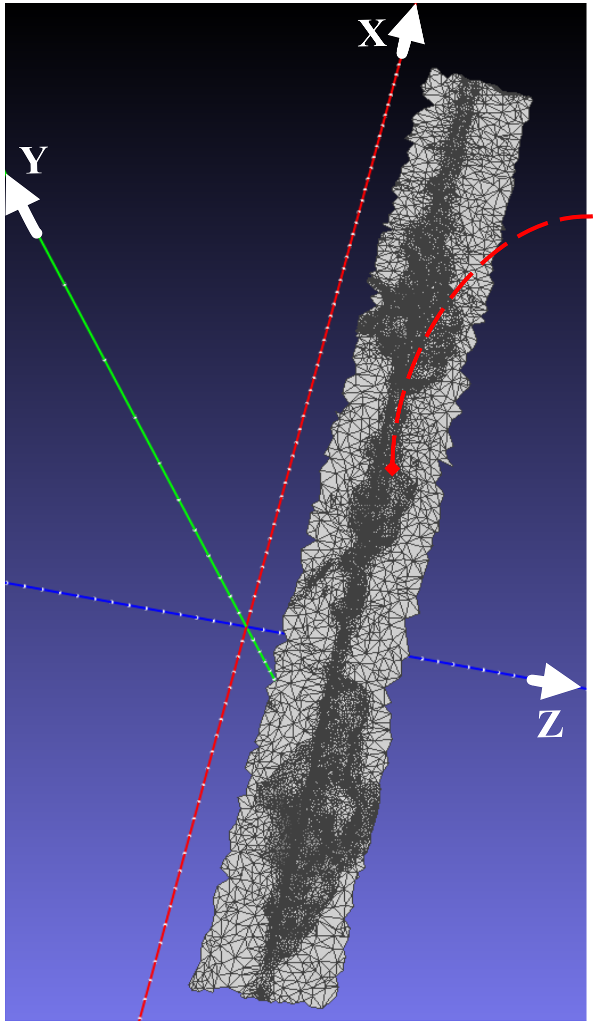
Step 1:

- Take multiple pictures of each saw cut
- Construct point cloud and dense model

Step 2:
Build Mesh model

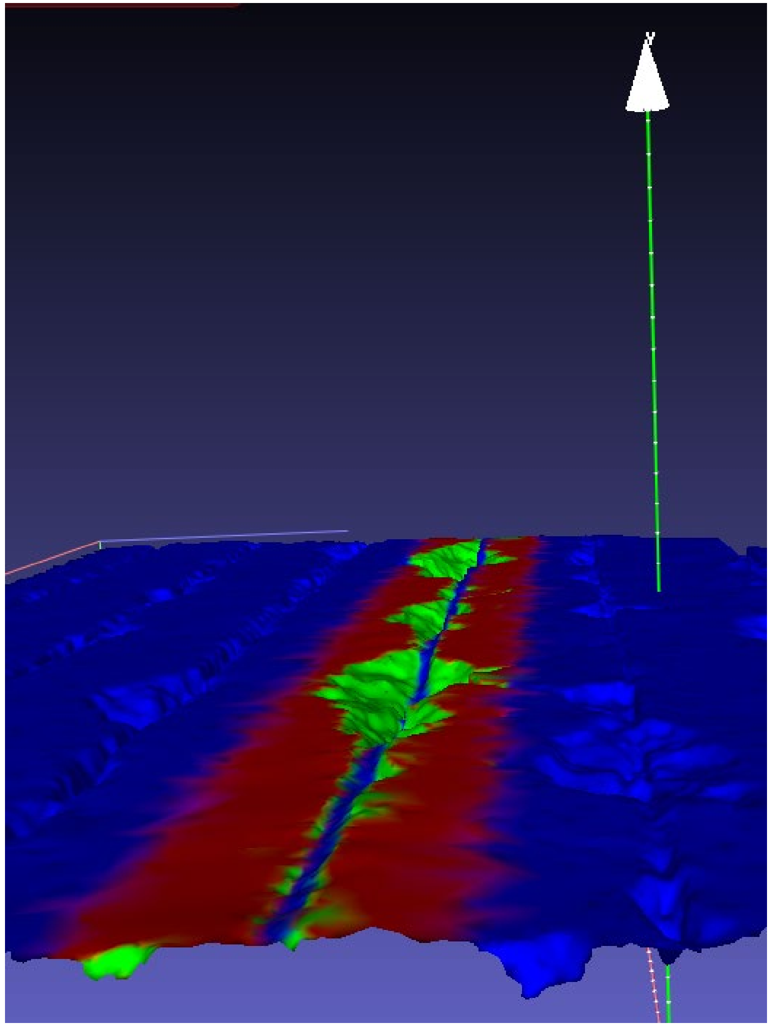
Step 3:
Compute surface area of damaged and undamaged elements

Mesh elements



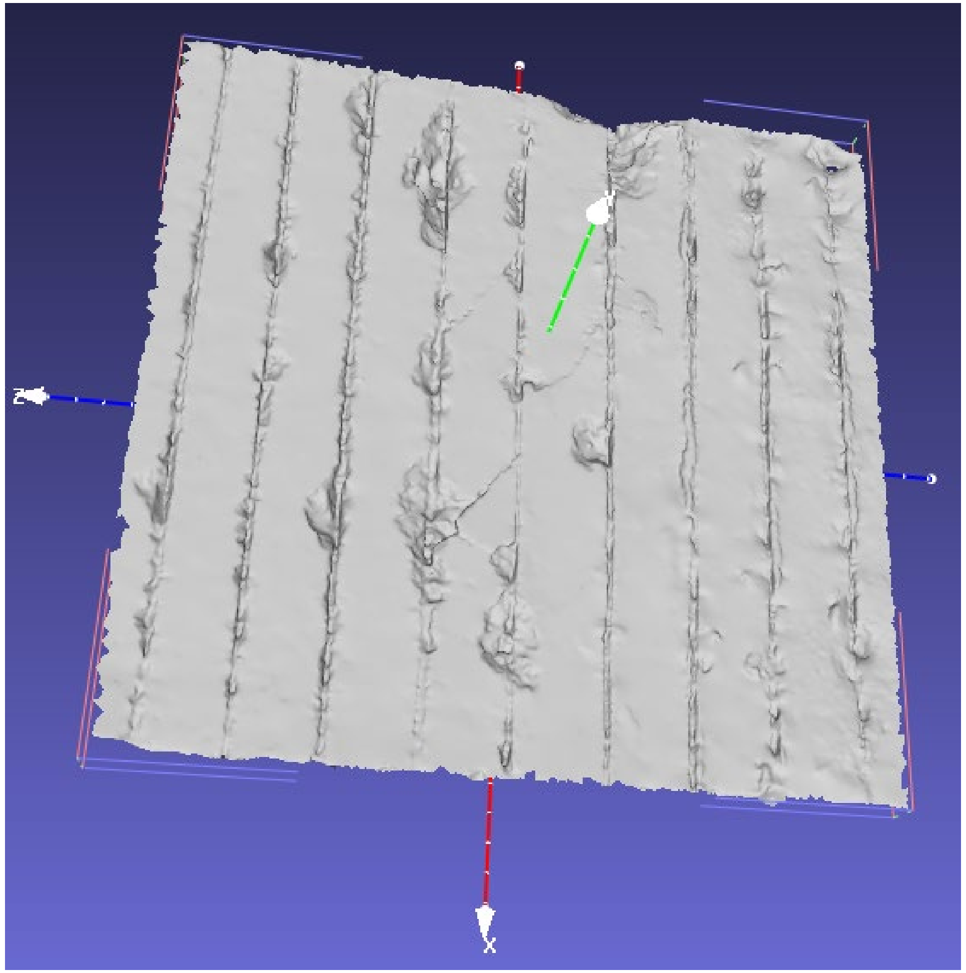
CV algorithm

Damage detection

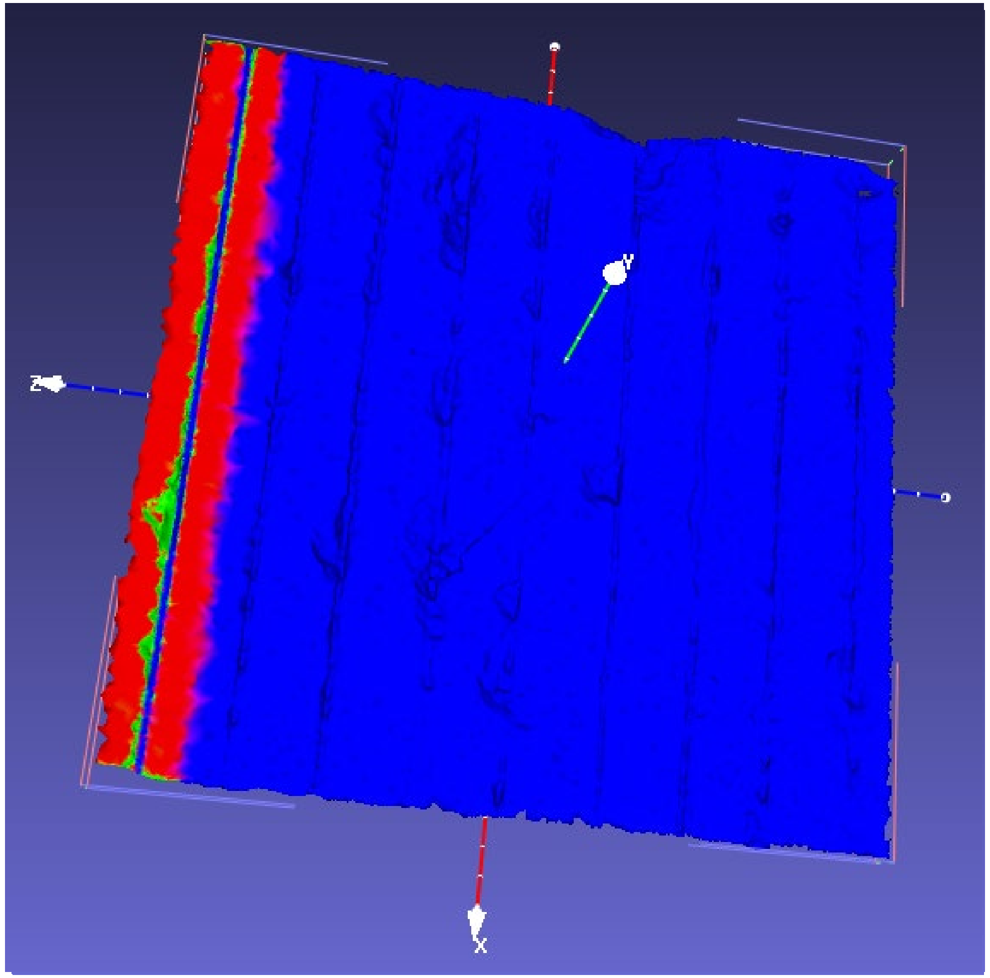


Quantification of Raveling Damage over Time

3D Meshed model



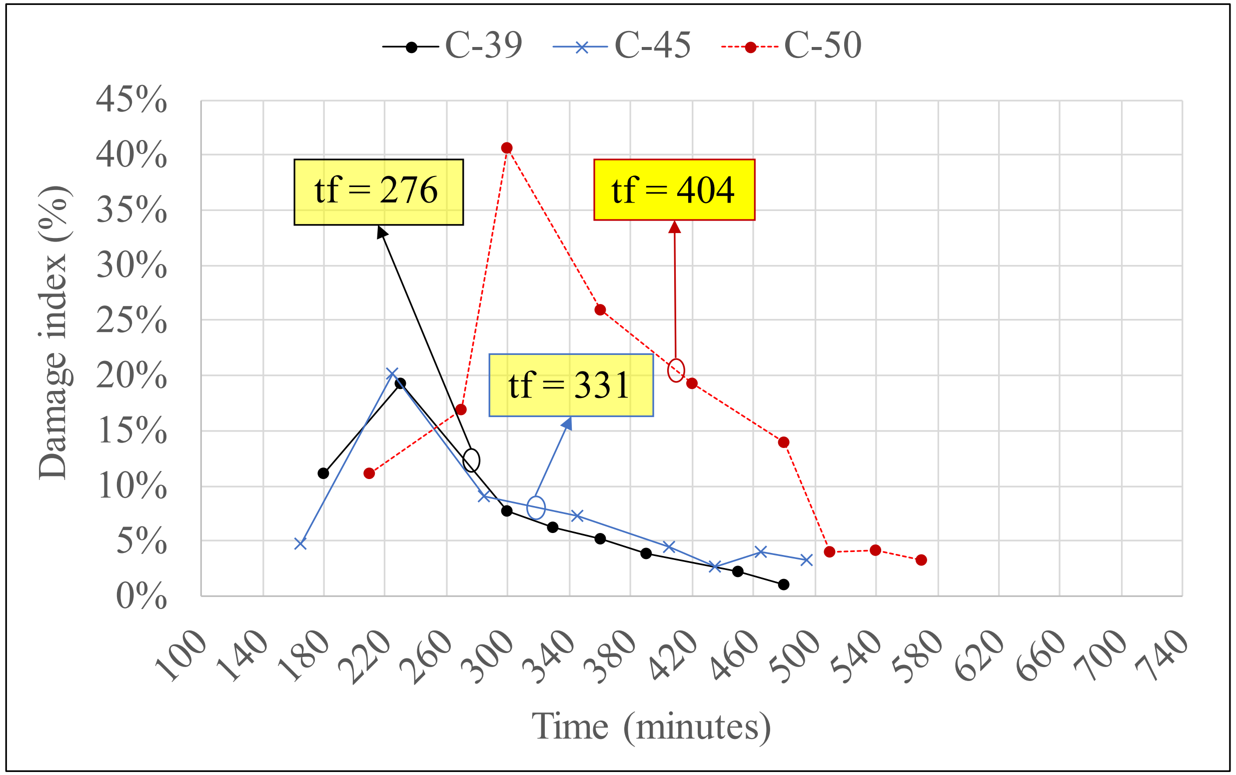
Damage development over Time



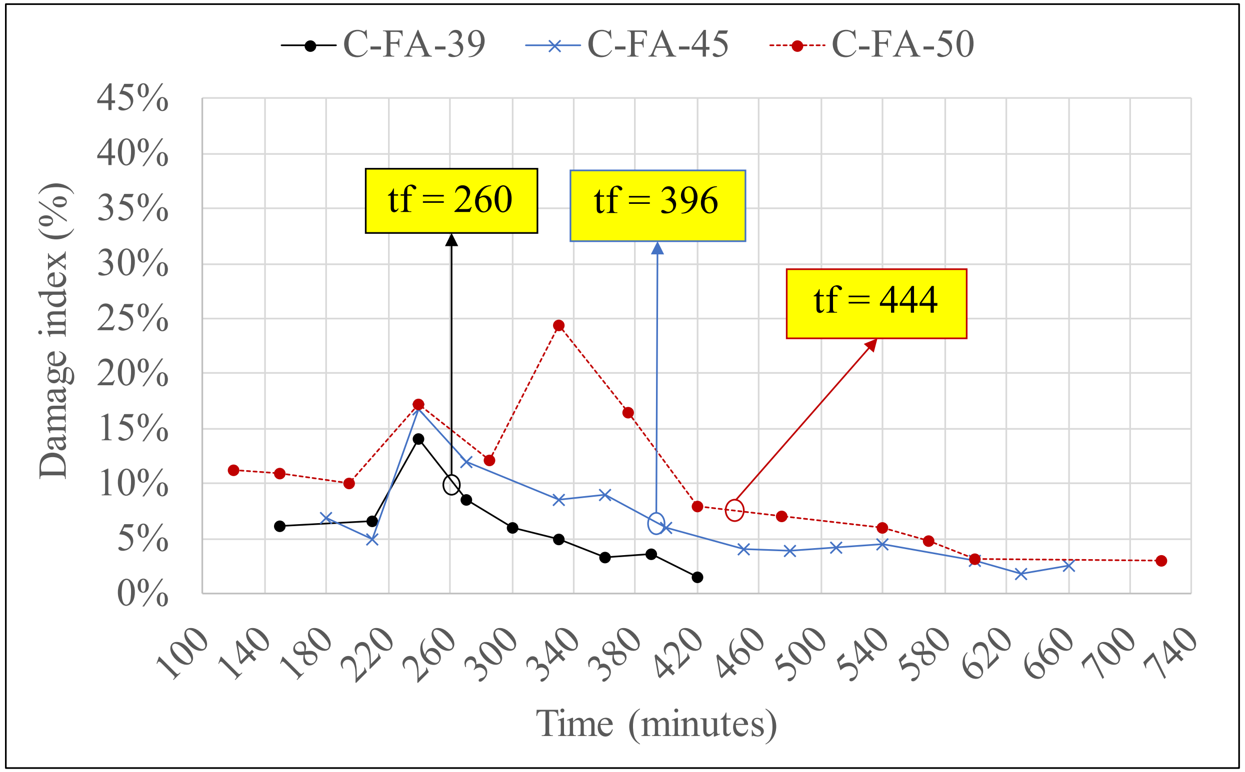
Time-variant Damage Index (DI) Plot

Joint area normalization:

$$\text{Damage index (DI)} = \frac{Surface\ area\ of\ damaged\ elements}{3 * 500mm * (Dmax\ or\ 25mm)} * 100\ (\%)$$



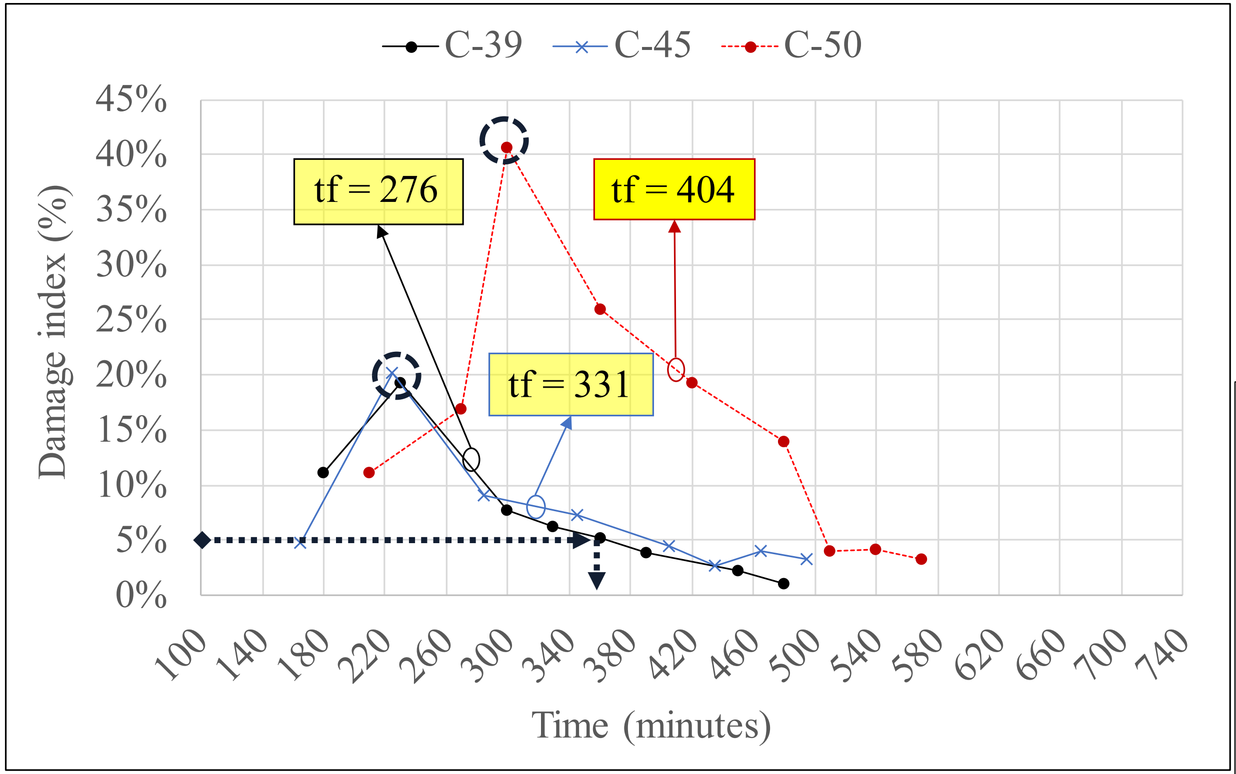
3 Portland cement concrete mixtures

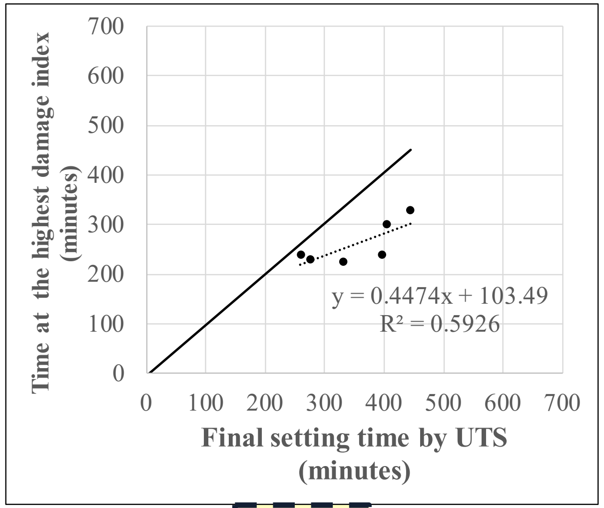


3 cement-fly ash concrete mixtures

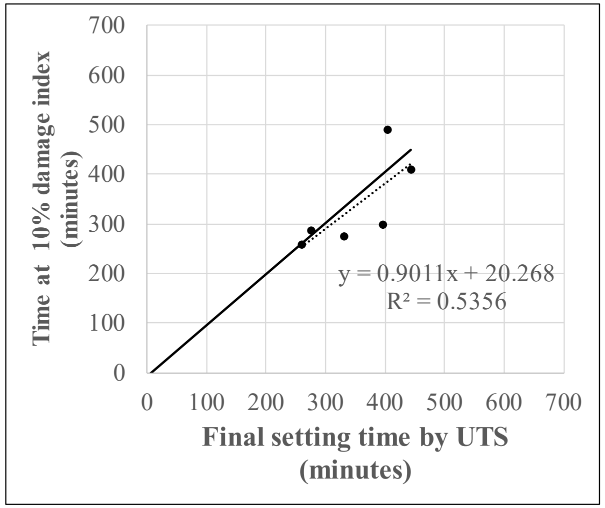
Relationship between Two Techniques

3 Portland cement concrete mixtures

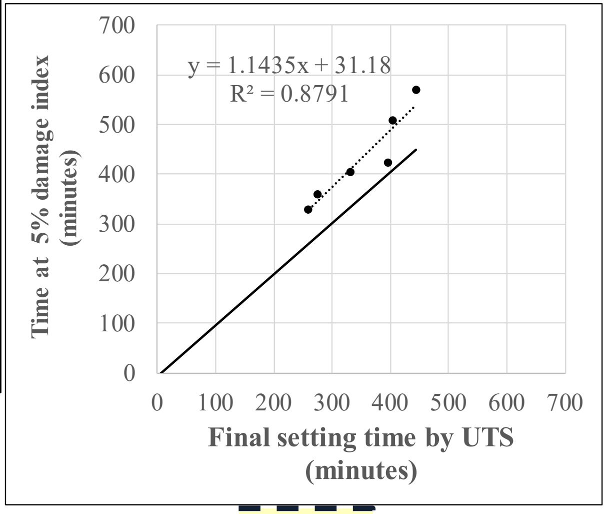




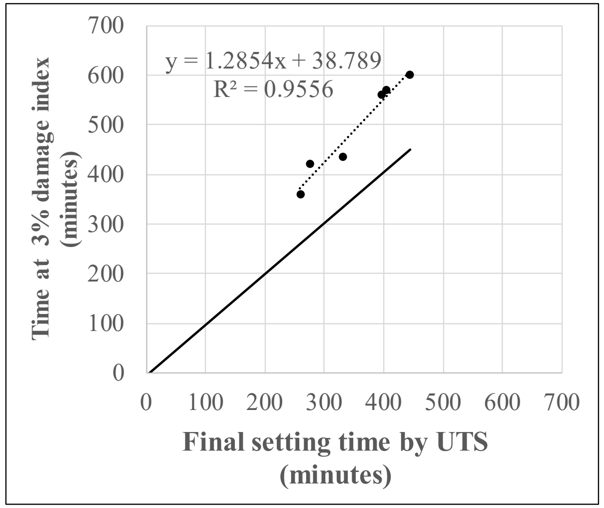
DI_{peak}



10%



5%

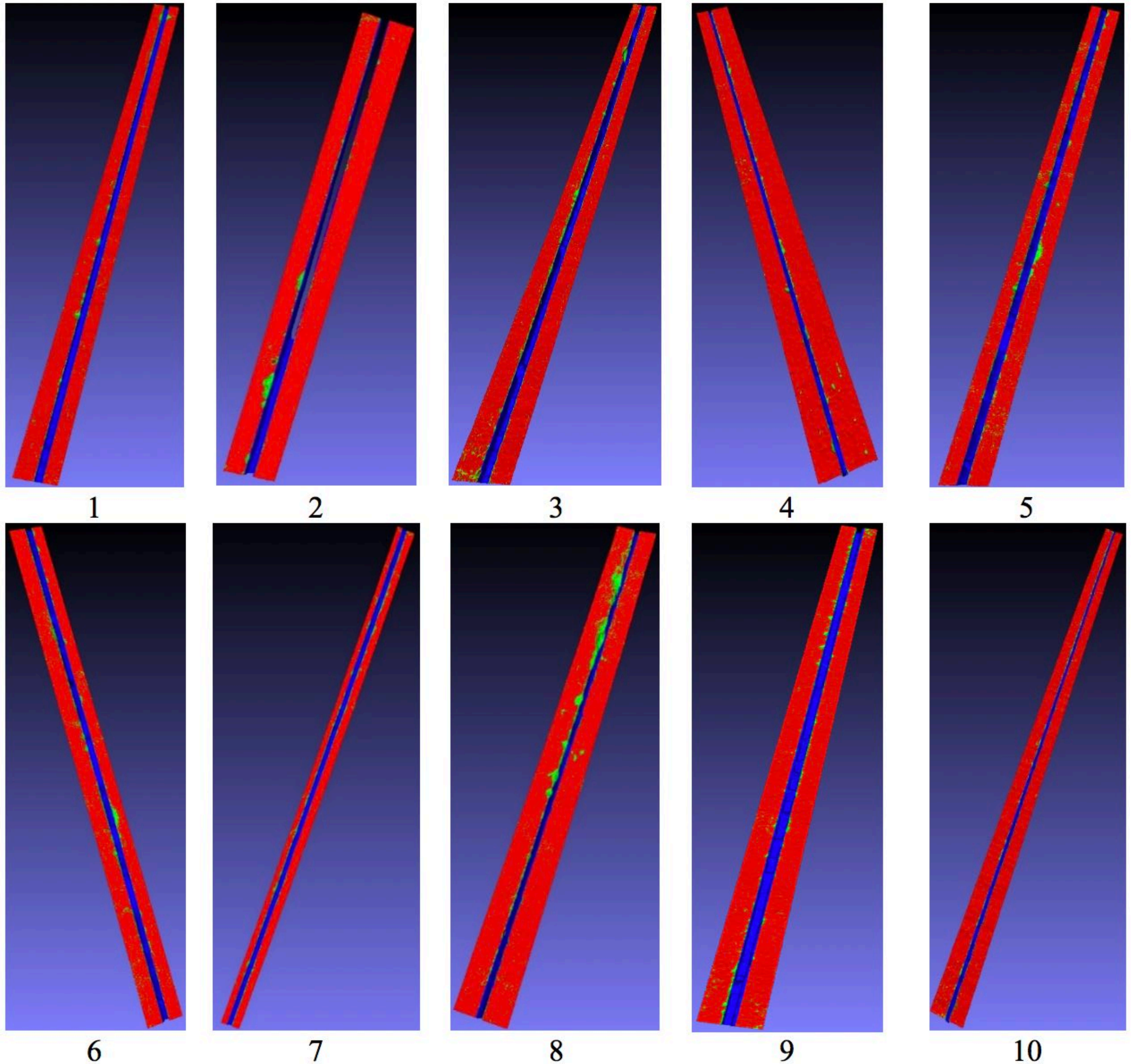


3%

Relationship between concrete final setting times by UTS and the time at (a) the peak DI (b) 10%, (c) 5%, and (d) 3% of post-DI curve

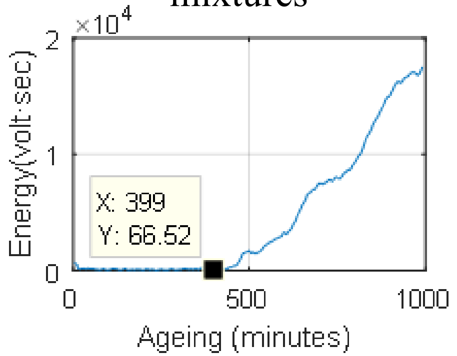
Field DI Results

Location	1	2	3	4	5	6	7	8	9	10	Mean	Standard deviation
DI (%)	2%	2%	2%	4%	2%	2%	2%	6%	2%	3%	3%	1.2%

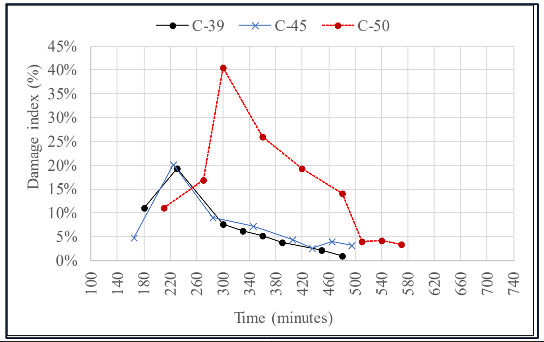


Determination of Sawcut Time Using UTS

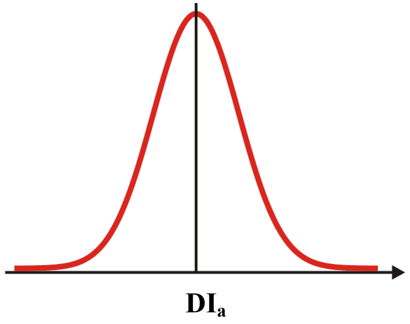
Determine the final setting time (t_f) using non-contact UTS of all mixtures



Construct damage index (DI) plots of all mixtures using CV-based technique



Determine the acceptable DI (DI_a) using CV-based technique and statistical data analysis

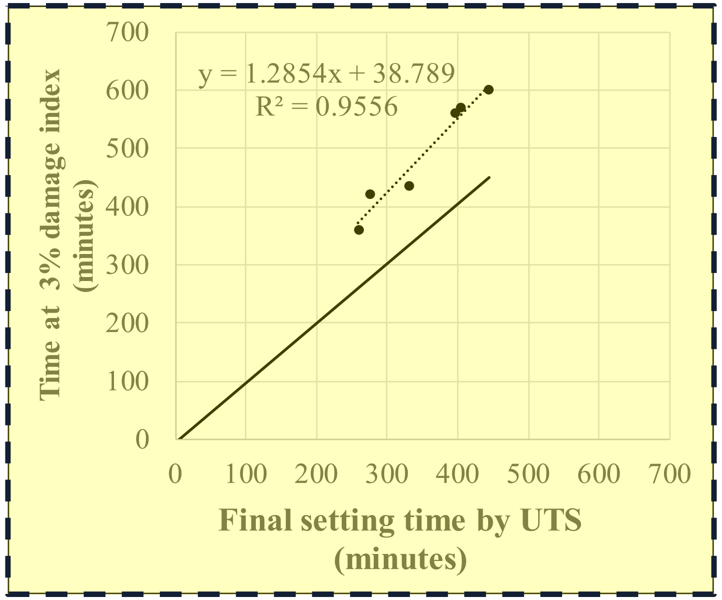


Establish sawcut timing t_s from DI_a

Establish relationship between t_f and t_s

$$t_s = 1.3 * t_f + 39$$

At acceptable damage index DIa = 3%



Conclusions

1. Lab or field method to predict the initiation time of (dry) saw-cutting that minimizes joint raveling

2. Non-contact ultrasonic testing technique (UTS) to estimate the final setting time (t_f):
   - t_f followed the expected trends with higher set time for higher w/cm and fly ash
   - **High reliability** (standard deviation = 21 minutes and coefficient of variation = 8%)

3. Improved CV-based technique was proposed to:
   - detect raveling damage along 3D reconstructed joint area
   - quantify the joint raveling through new damage index (DI)

4. Sawcut initiation time (t_s) at acceptable DI of 3% = $1.3*t_f + 39$ minutes

5. Non-contact UTS & image-based estimation of raveling provide a useful tool:
   - QC/QA and less experienced personnel (e.g., new field engineers or sawcut operators)
   - Provides acceptable criteria between engineers, contractors, and saw operators

Thank you!

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Automatic damage detection using DL

Analyzing Mesh Using Histogram

Step 1:

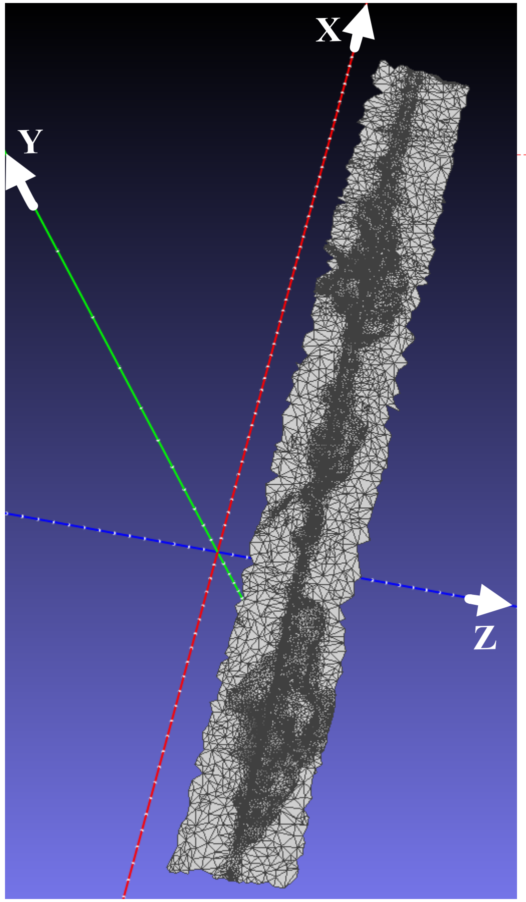
- Taking multiple pictures of samples
- Construct point cloud and dense model

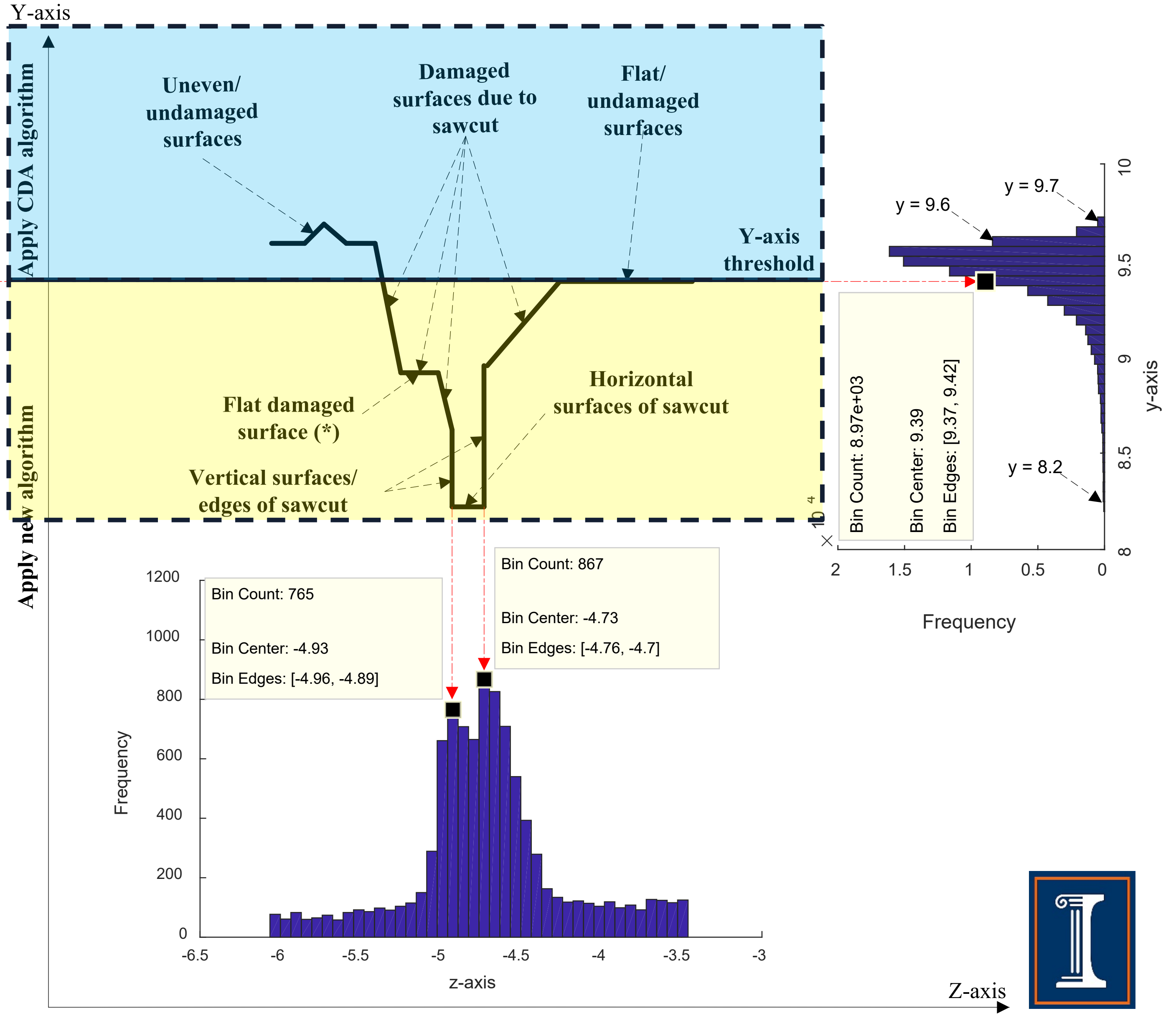
Step 2:

Build Mesh model

Step 3:

Compute surface area of damaged and undamaged elements





Analyzing Mesh using Surface Normal

Step 1:

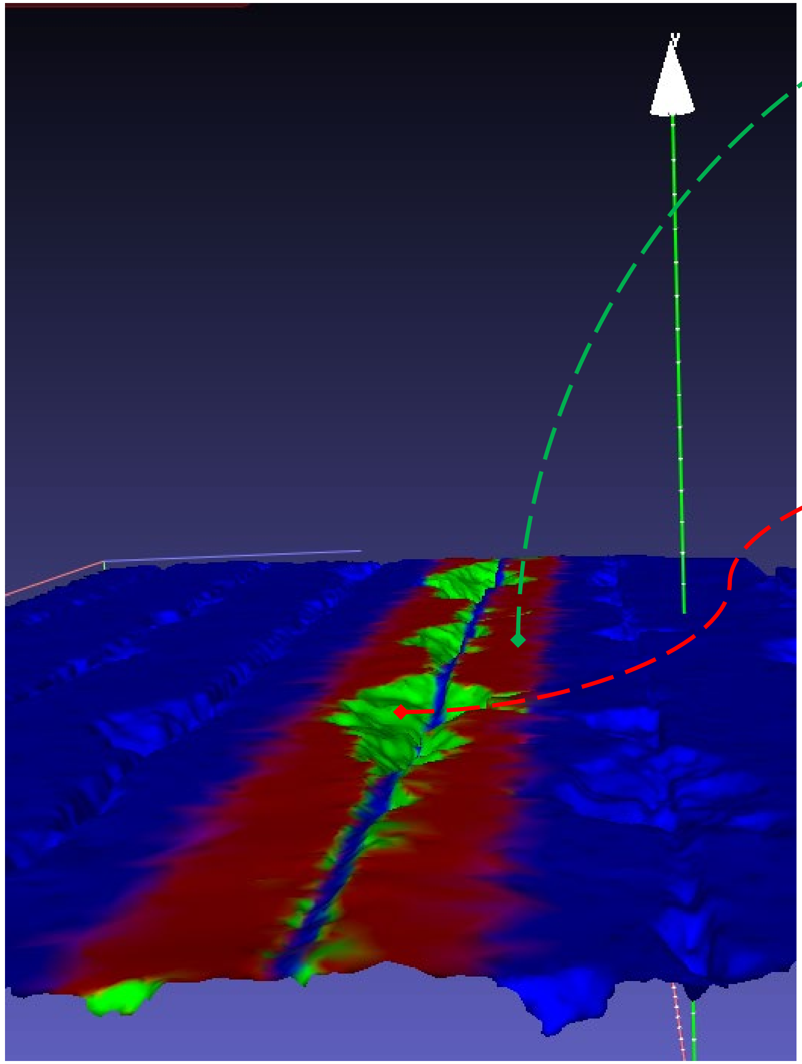
- Take multiple pictures of each saw cut
- Construct point cloud and dense model

Step 2:

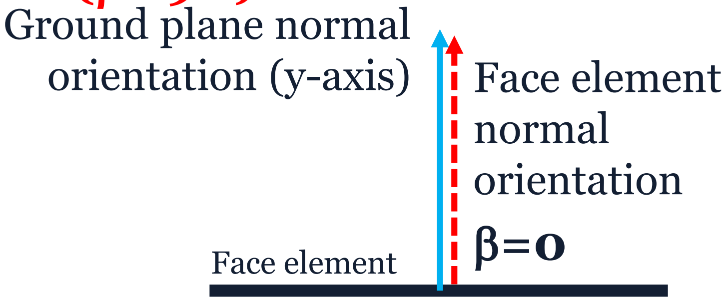
Build Mesh model

Step 3:

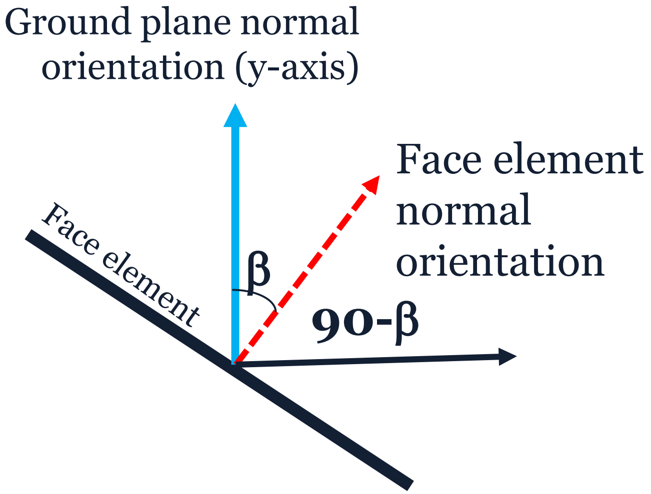
Compute surface area of damaged and undamaged elements



Flat surface - undamaged (β=90)



Inclined surface - Damaged ($\beta \neq$90)



(Torok, Golparvar-Fard et al. 2013)