Prediction and Measurement of Slab Construction Load of Wall-type Residential Building

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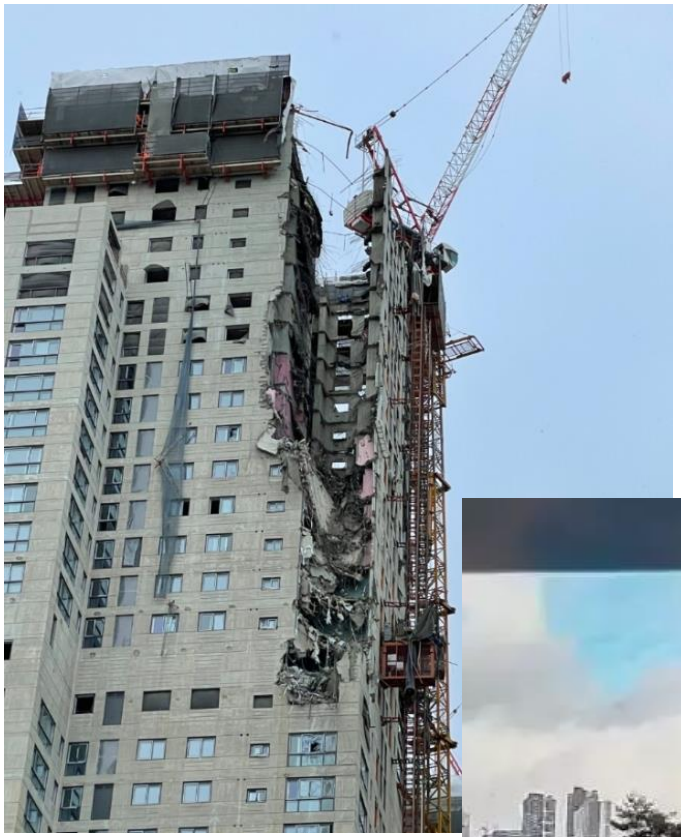
CONTENTS

1. Introduction

✓ **Gwangju**

Residential Building Collapse Accident



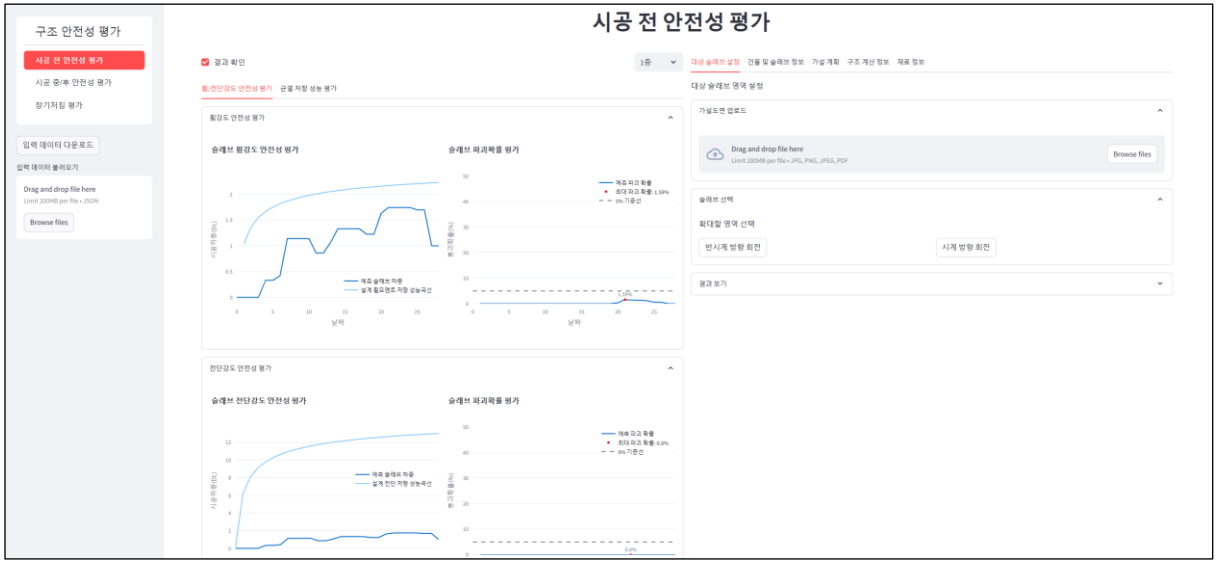
✓ **Incheon**

Parking Garage Collapse Accident

1. Introduction

✓ Development of Structural Safety Assessment Software

- Construction load model
- Verification of model through comparison with field measurement
- Cracking and load resistance of early-aged slab during construction
- Failure probability prediction of early-aged slab during construction

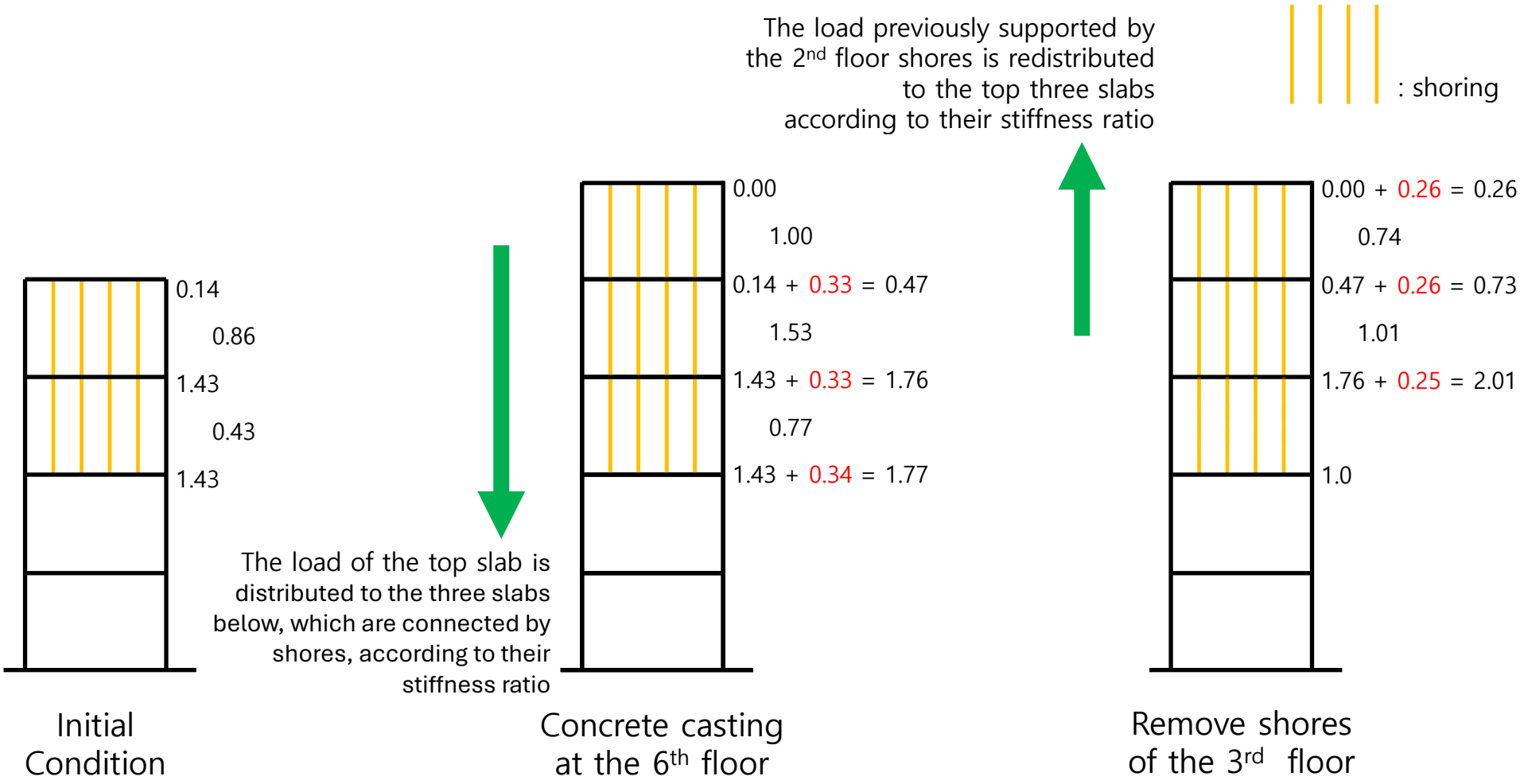


2. Basic Concept of Load Transfer during Construction

* Assumption:
  same slab stiffness
  three levels of shores

✓ Construction Load?

: Slab load transferred through form shores that support upper slab weight



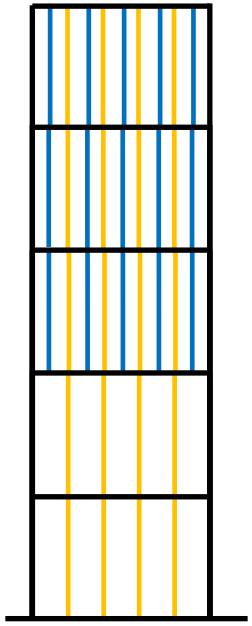
3. Construction Load Prediction Model

✓ Verification Site Information

: Regualar support : Temporary support

Planned Construction Schedule

- Construction cycle of each floor : 7 days
- Number of floors supported by shores : 3 floors
- Removal of temporary support : 4 days after casting the top floor
- Removal of regular support : 5 days after pouring the top floor



Cast 6th floor

Remove temporary supports in 5th floor

Remove temporary supports in 4th floor

Remove regular supports in 3rd floor

Remove regular supports in 2nd floor

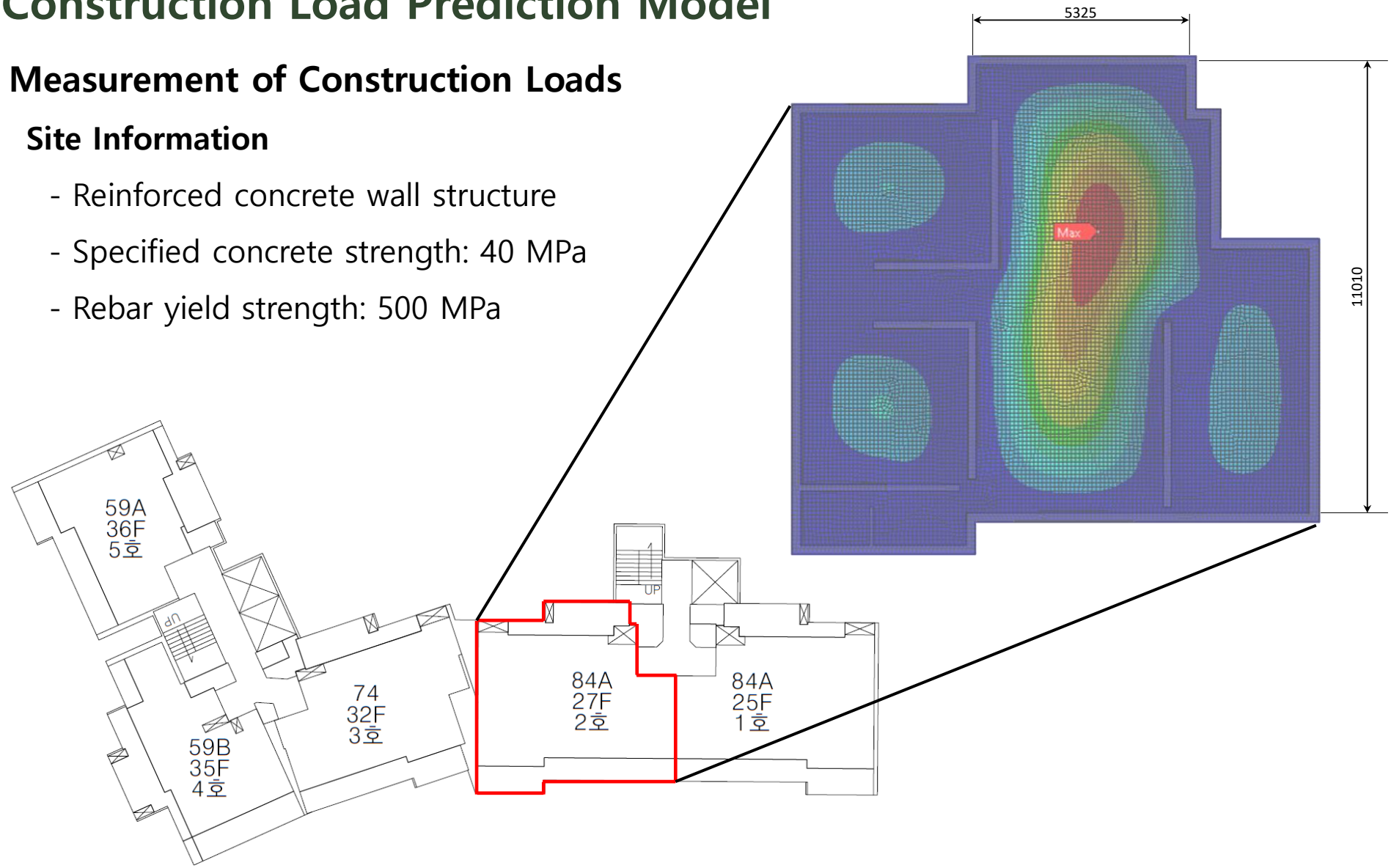
Remove regular supports in 1st floor

3. Construction Load Prediction Model

✓ Measurement of Construction Loads

Site Information

- Reinforced concrete wall structure
- Specified concrete strength: 40 MPa
- Rebar yield strength: 500 MPa

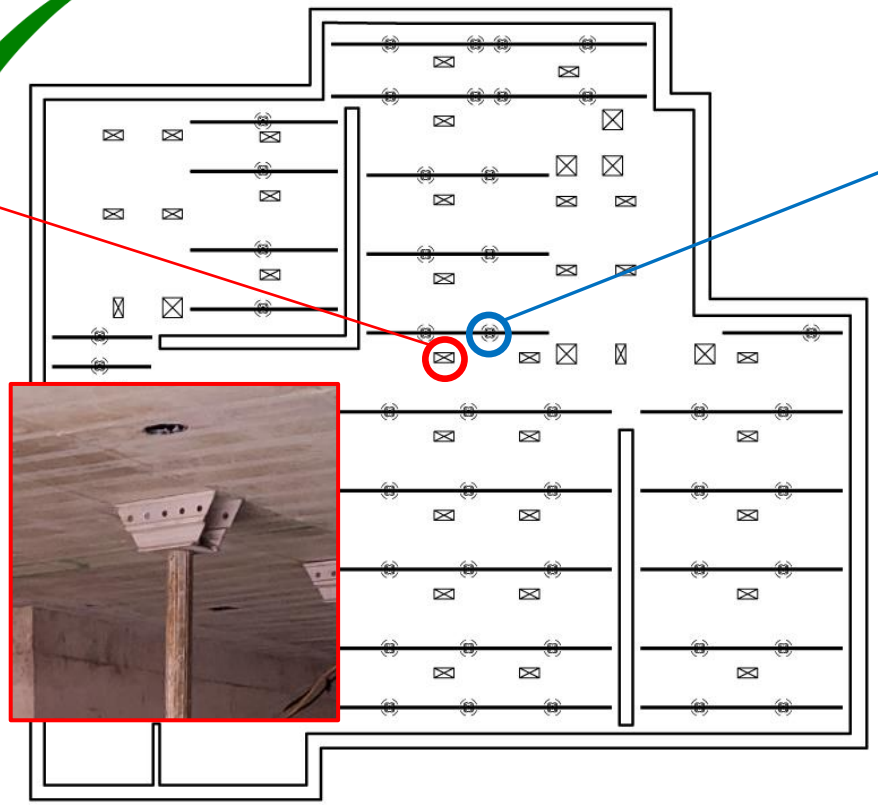


3. Construction Load Prediction Model

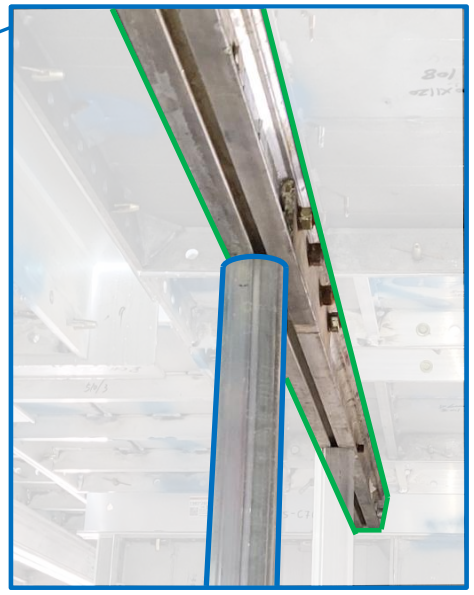
✓ Measurement of axial shore force

Regular support

- Supporting the upper slab
- Remains in place even after removing the slab formwork



Temporary support



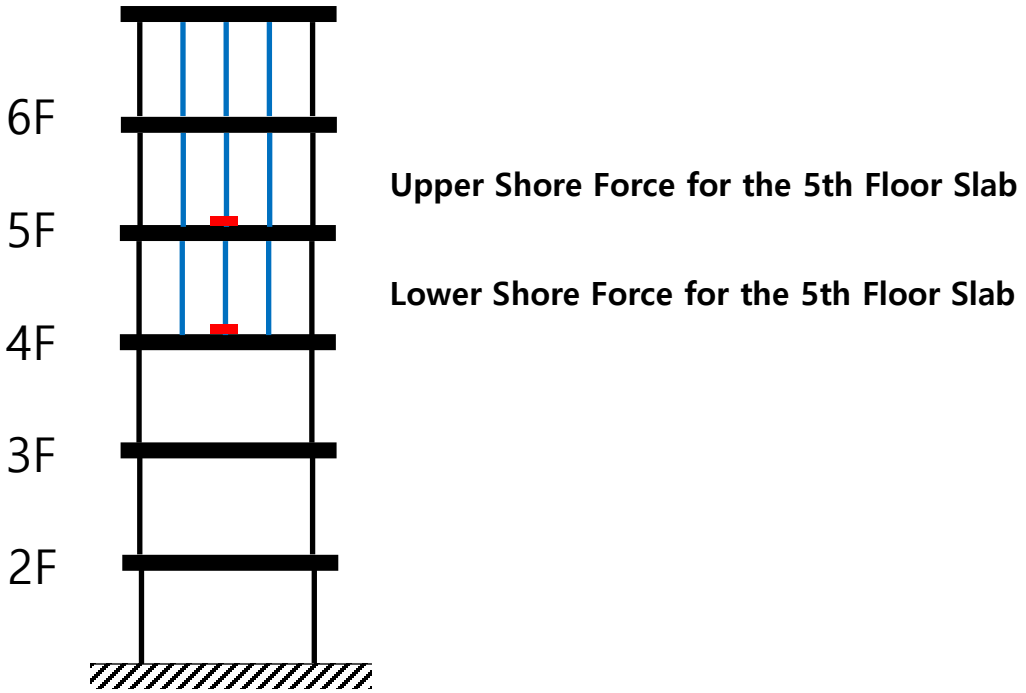
- Supporting the rail that supports the slab formwork
- Removed together when removing the slab formwork

3. Construction Load Prediction Model

✓ Conversion to Construction Load

Construction Load = Upper shore force + Self-weight of slab – Lower shore force

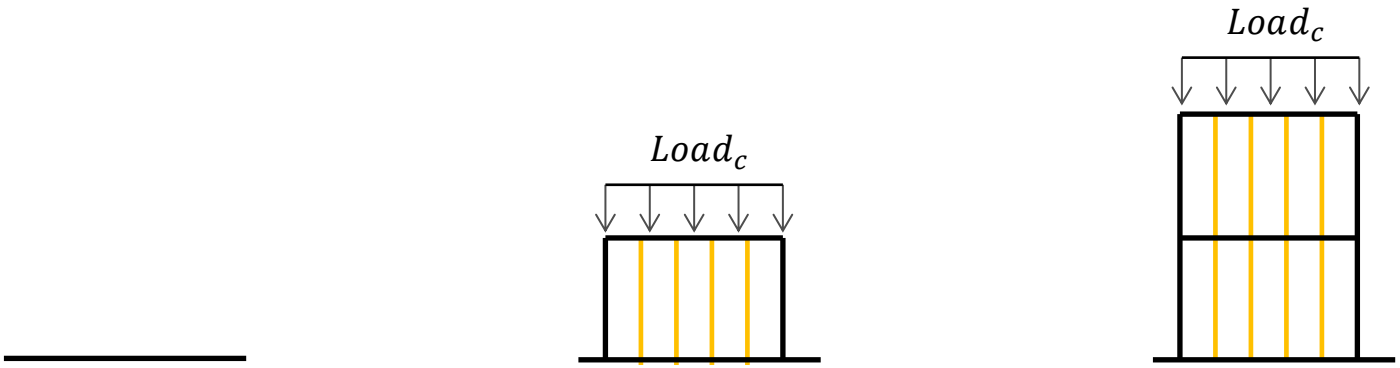
* At this time, the shore force should be converted to DL (Dead Load) units for calculation



3. Construction Load Prediction Model

✓ Calculation of Construction Load for Lower Floors

: Regualar support

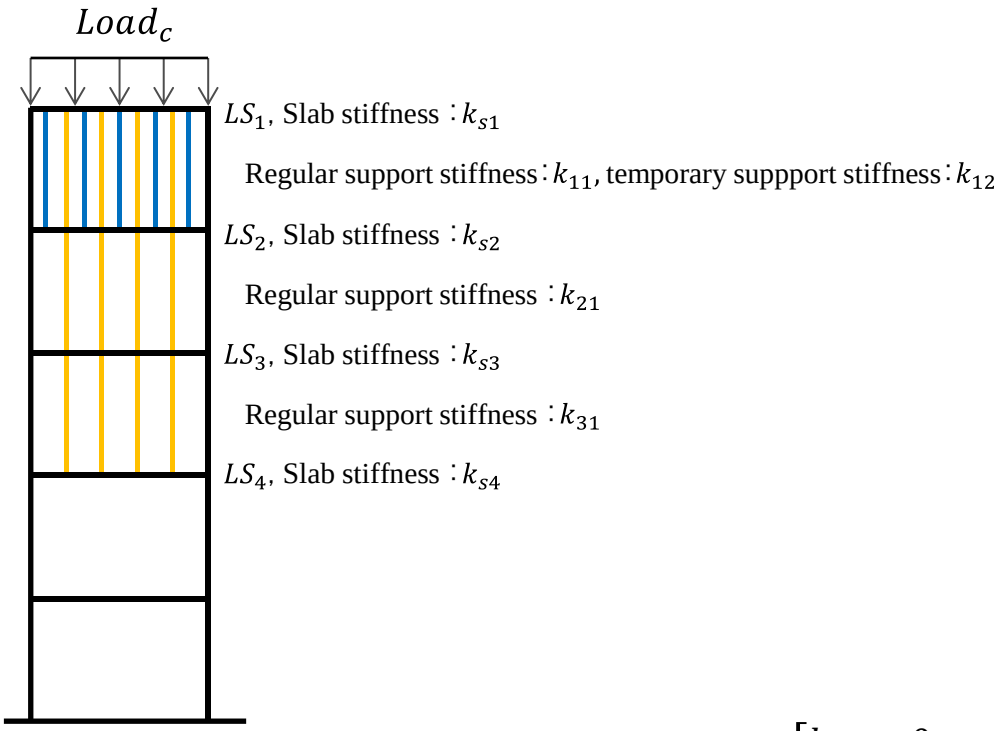


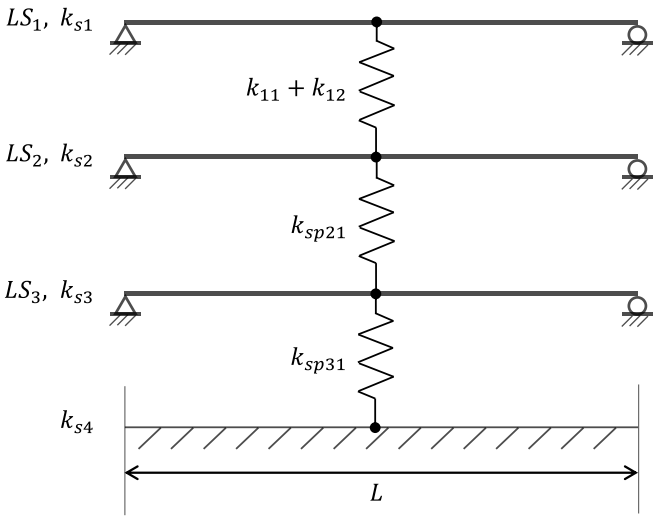
3. Calculation of Construction Load

✓ Concrete casting of slab

: Regualar support

: Temporary support





$$\begin{pmatrix} DL+LL \\ 0 \\ 0 \end{pmatrix} = [K_{ff}] \begin{pmatrix} v_2 \\ v_3 \\ v_4 \end{pmatrix}, \quad \begin{pmatrix} LS_2 \\ LS_3 \\ LS_4 \end{pmatrix} = [K_{fsl}] \begin{pmatrix} v_2 \\ v_3 \\ v_4 \end{pmatrix}$$

$$\begin{pmatrix} LS_2 \\ LS_3 \\ LS_4 \end{pmatrix} = [K_{fsl}] \begin{pmatrix} v_2 \\ v_3 \\ v_4 \end{pmatrix} = [K_{fsl}] [K_{ff}]^{-1} \begin{pmatrix} DL+LL \\ 0 \\ 0 \end{pmatrix}$$

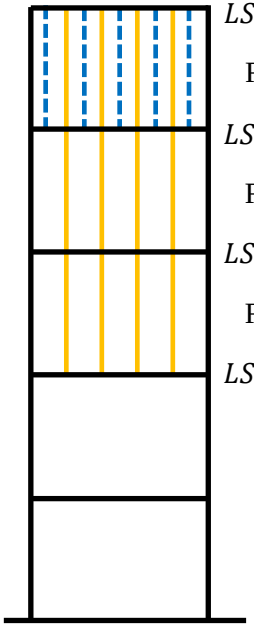
$$[K_{fsl}] = \begin{bmatrix} k_{s2} & 0 & 0 \\ 0 & k_{s3} & 0 \\ 0 & 0 & k_{s4} \end{bmatrix} \quad [K_{ff}] = \begin{bmatrix} k_{s2}+k_{21} & -k_{21} & 0 \\ -k_{21} & k_{s3}+k_{21}+k_{31} & -k_{31} \\ 0 & -k_{31} & k_{s4}+k_{31} \end{bmatrix}$$

3. Calculation of Construction Load

✓ Removal of temporary supports

STEP 1.

: Regualar support : Removed temporary support



LS_1, Slab stiffness : k_{s1}

Regular support stiffness: k_{11}, temporary suppport stiffness: k_{12}

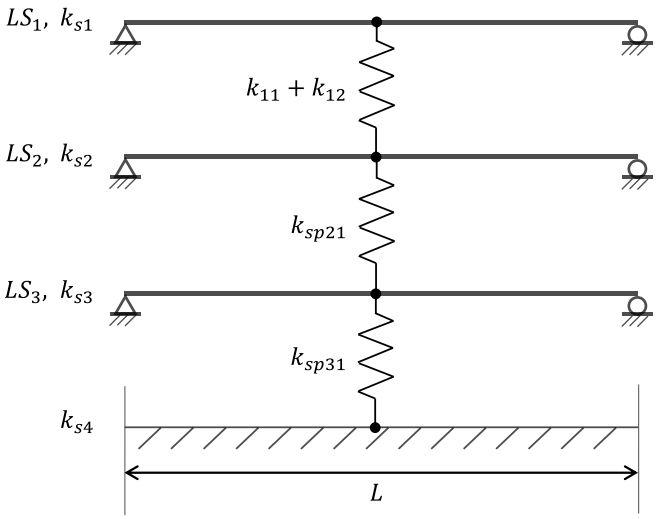
LS_2, Slab stiffness : k_{s2}

Regular support stiffness : k_{21}

LS_3, Slab stiffness : k_{s3}

Regular support stiffness : k_{31}

LS_4, Slab stiffness : k_{s4}



$$\begin{pmatrix} LS_2 \\ LS_3 \\ LS_4 \end{pmatrix} = [K_{fsl}] \begin{pmatrix} v_2 \\ v_3 \\ v_4 \end{pmatrix} = [K_{fsl}] [K_{ff}]^{-1} \begin{pmatrix} -(DL\left(\frac{k_{12}}{k_{11}+k_{12}}\right)+LL) \\ 0 \\ 0 \end{pmatrix}$$

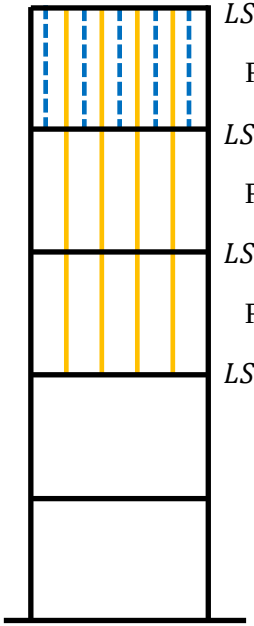
$$[K_{fsl}] = \begin{bmatrix} k_{s2} & 0 & 0 \\ 0 & k_{s3} & 0 \\ 0 & 0 & k_{s4} \end{bmatrix} \quad [K_{ff}] = \begin{bmatrix} k_{s2}+k_{21} & -k_{21} & 0 \\ -k_{21} & k_{s3}+k_{21}+k_{31} & -k_{31} \\ 0 & -k_{31} & k_{s4}+k_{31} \end{bmatrix}$$

3. Calculation of Construction Load

✓ Removal of temporary supports

STEP 2.

: Regualar support : Removed temporary support



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Regular support stiffness: k_{11}, temporary suppport stiffness: k_{12}

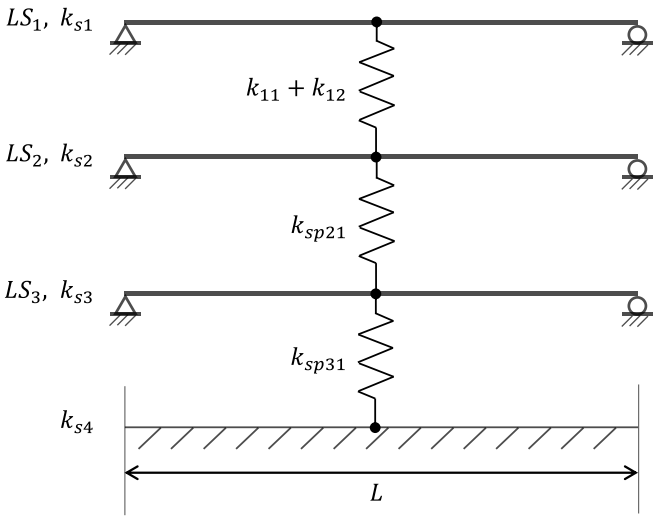
LS_2, Slab stiffness : k_{s2}

Regular support stiffness : k_{21}

LS_3, Slab stiffness : k_{s3}

Regular support stiffness : k_{31}

LS_4, Slab stiffness : k_{s4}



$$\begin{pmatrix} LS_1 \\ LS_2 \\ LS_3 \\ LS_4 \end{pmatrix} = [K_{fsl}] \begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{pmatrix} = [K_{fsl}]\,[K_{ff}]^{-1} \begin{pmatrix} DL\left(\frac{k_{12}}{k_{11}+k_{12}}\right) \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$[K_{fsl}] = \begin{bmatrix} k_{s1} & 0 & 0 & 0 \\ 0 & k_{s2} & 0 & 0 \\ 0 & 0 & k_{s3} & 0 \\ 0 & 0 & 0 & k_{s4} \end{bmatrix}$$

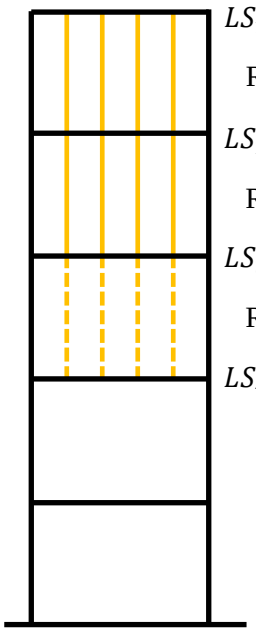
$$[K_{ff}] = \begin{bmatrix} k_{s1}+k_{11} & -k_{11} & 0 & 0 \\ -k_{11} & k_{s2}+k_{11}+k_{21} & -k_{21} & 0 \\ 0 & -k_{21} & k_{s3}+k_{21}+k_{31} & -k_{31} \\ 0 & 0 & -k_{31} & k_{s4}+k_{32} \end{bmatrix}$$

3. Calculation of Construction Load

✓ Removal of regular supports

: Regualar support

: Removed regular support



LS_1, Slab stiffness : k_{s1}

Regular support stiffness : k_{11}

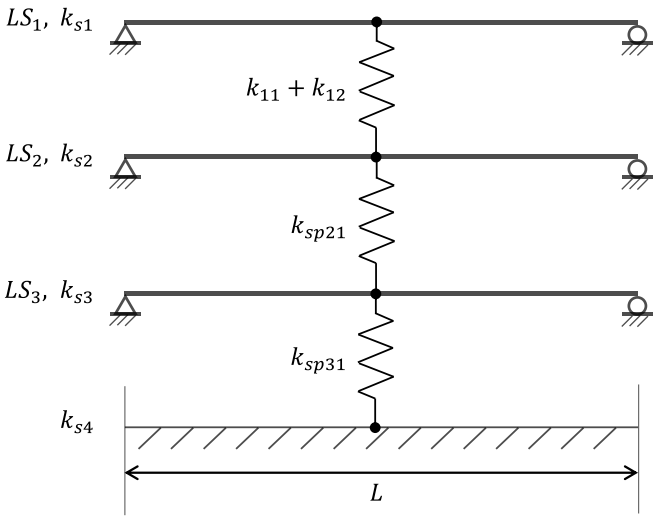
LS_2, Slab stiffness : k_{s2}

Regular support stiffness : k_{21}

LS_3, Slab stiffness : k_{s3}

Regular support stiffness : k_{31}

LS_4, Slab stiffness : k_{s4}



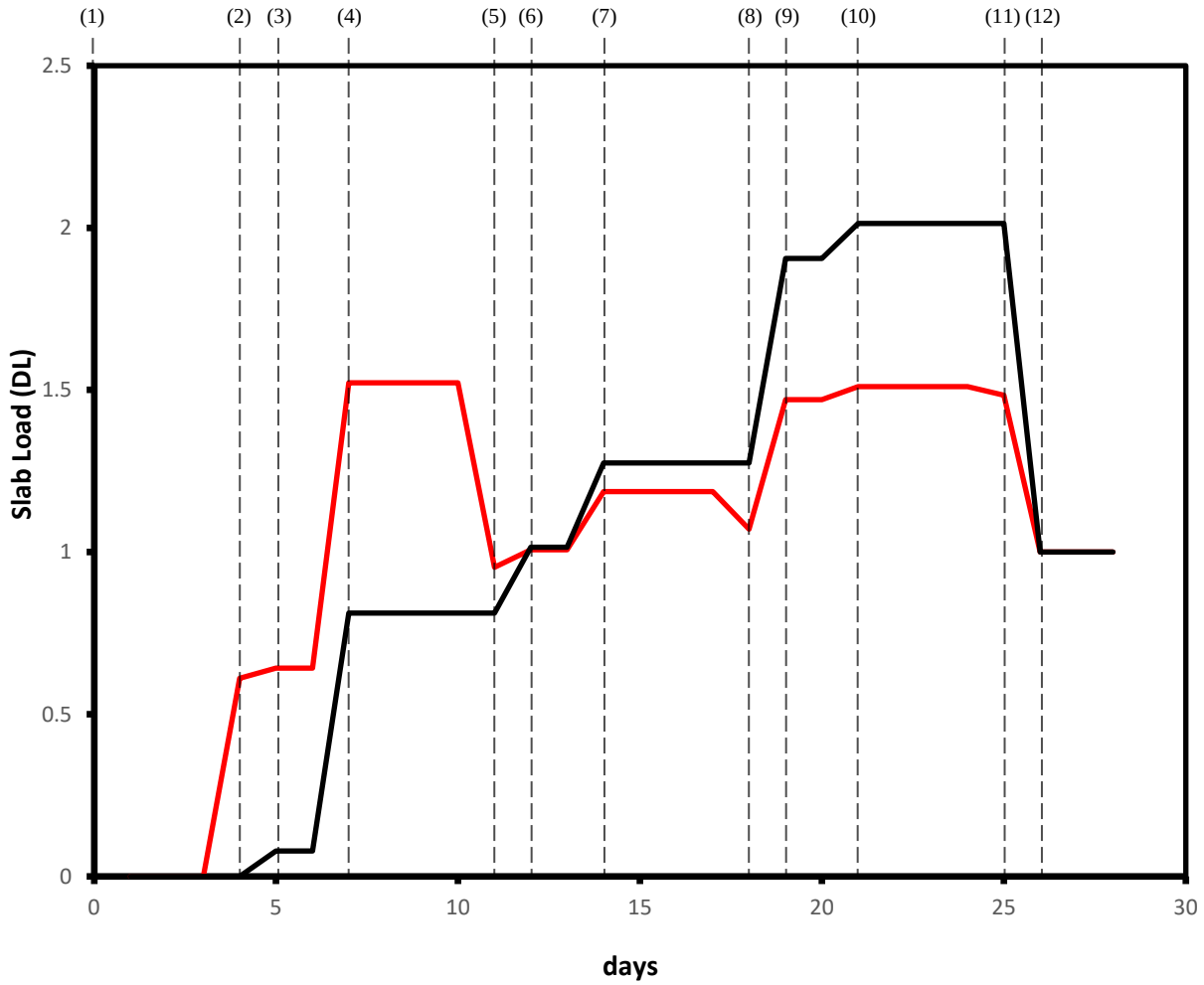
$$\begin{pmatrix} LS_1 \\ LS_2 \\ LS_3 \end{pmatrix} = [K_{fsl}] \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} = [K_{fsl}] [K_{ff}]^{-1} \begin{pmatrix} 0 \\ 0 \\ Load_{sh} \end{pmatrix}$$

$$[K_{fsl}] = \begin{bmatrix} k_{s1} & 0 & 0 \\ 0 & k_{s2} & 0 \\ 0 & 0 & k_{s3} \end{bmatrix}$$

$$[K_{ff}] = \begin{bmatrix} k_{s1} + k_{11} & -k_{11} & 0 \\ -k_{11} & k_{s2} + k_{11} + k_{21} & -k_{21} \\ 0 & -k_{21} & k_{s3} + k_{21} \end{bmatrix}$$

3. Calculation of Construction Load

✓ Prediction result

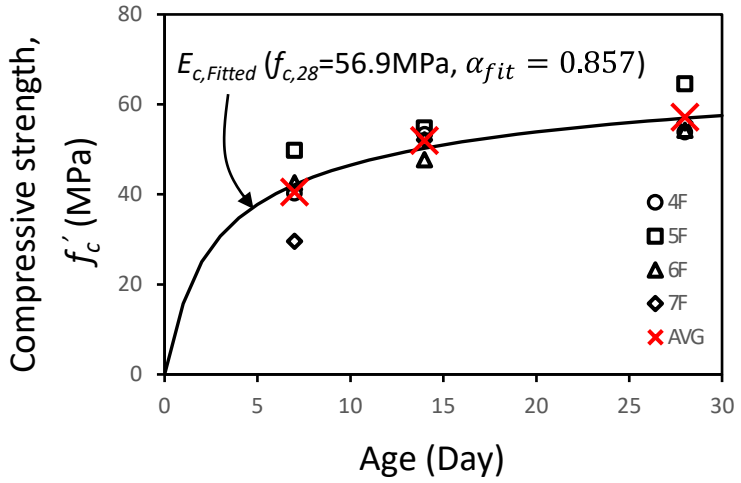


With temporary supports
Without temporary supports

(1) Cast 4th floor
(2) Remove temporary supports in 3rd floor
(3) Remove regular supports in 1st floor
(4) Cast 5th floor
(5) Remove aluminum supports in 4th floor
(6) Remove regular supports in 2nd floor
(7) Cast 6th floor
(8) Remove aluminum supports in 5th floor
(9) Remove regular supports in 3rd floor
(10) Cast 7th floor
(11) Remove aluminum supports in 6th floor
(12) Remove regular supports in 4th floor

3. Calculation of Construction Load

✓ Prediction result



$$f_c(t) = \exp\left\{\alpha_{fit} \cdot 0.35\left(1 - \sqrt{\frac{28}{t}}\right)\right\} f_{c28}$$

4F: $f_{c28} = 56$ MPa, $\alpha_{fit} = 0.75$

5F: $f_{c28} = 65$ MPa, $\alpha_{fit} = 0.90$

6F: $f_{c28} = 54$ MPa, $\alpha_{fit} = 0.85$

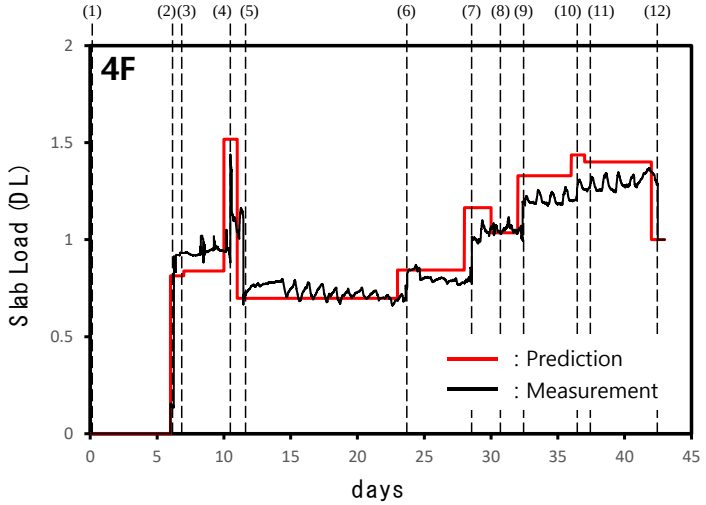
7F: $f_{c28} = 56$ MPa, $\alpha_{fit} = 1.00$

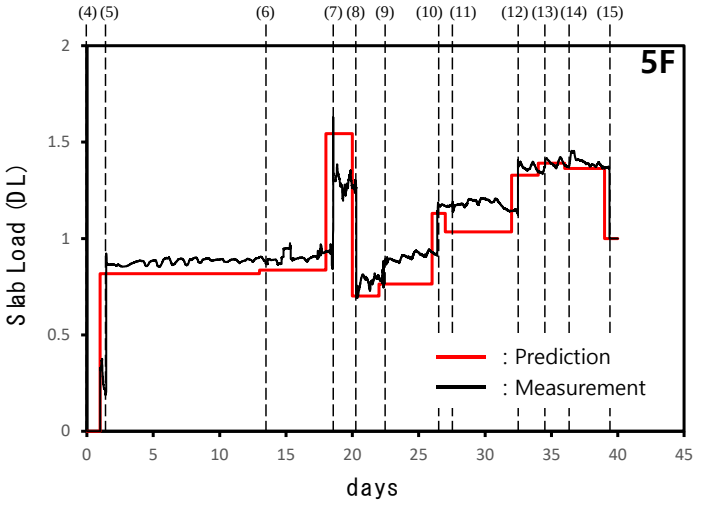
Construction schedule for concrete casting and shoring

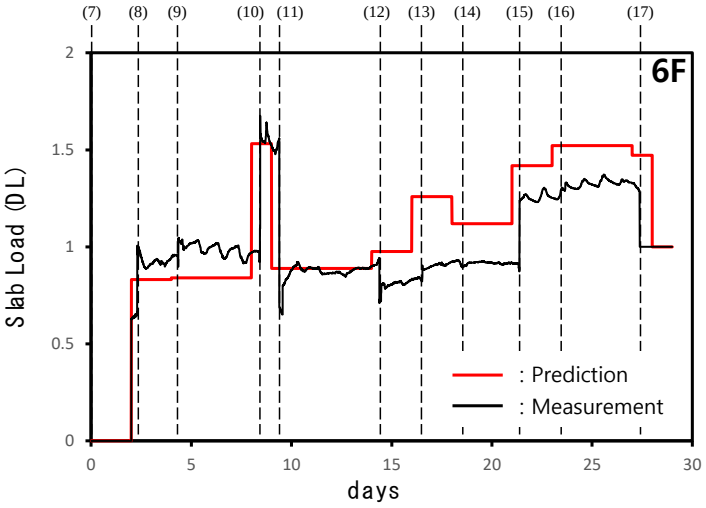
Floor	Concrete casting	Installation		Removal	
		Regular	Temporary	Regular	Temporary
3F	-	Aug 22	Aug 22	09/24	Aug 29
4F	Aug 23	Aug 30	Aug 30	Oct 05	Sep 3
5F	Sep 2	Sep 16	Sep 16	Oct 11	Sep 22
6F	Sep 20	Sep 26	Sep 26	Oct 27	Sep 29
7F	Sep 28	-		-	

3. Calculation of Construction Load

✓ Comparison of results







(1) Cast 4th floor
(2) Remove temporary supports in 3rd floor
(3) Remove regular supports in 1st floor
(4) Cast 5th floor
(5) Remove temporary supports in 4th floor
(6) Remove regular supports in 2nd floor
(7) Cast 6th floor
(8) Remove temporary supports in 5th floor
(9) Remove regular supports in 3rd floor
(10) Cast 7th floor
(11). Remove temporary supports in 6th floor
(12) Remove regular supports in 4th floor
(13) Cast 8th floor
(14) Remove temporary supports in 7th floor
(15) Remove regular supports in 5th floor
(16). Cast 9th floor
(17). Remove temporary supports in 8th floor
Remove regular supports in 6th floor

4. Structural Safety Assessment of Slab

✓ **Load corresponding to slab strength development during construction (Capacity)**

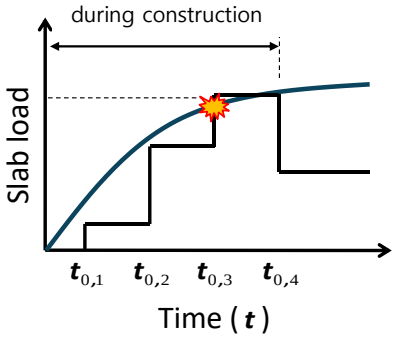
$$\phi_c \boldsymbol{R}_s \geq \gamma_c \boldsymbol{C}_t\,, \quad \boldsymbol{R}_s = \boldsymbol{R}_n(t)\,, \quad \boldsymbol{R}_n(t) = \alpha(t)\frac{\gamma_D \boldsymbol{D} + \gamma_L \boldsymbol{L}}{\phi}$$

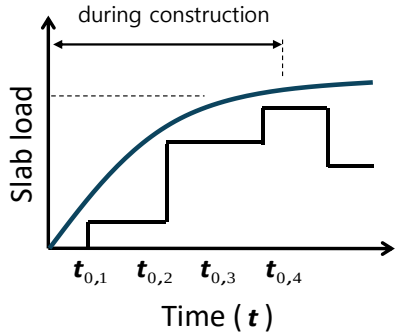
$$\rightarrow \quad \frac{\boldsymbol{C}_t}{\boldsymbol{D}} \leq \frac{\phi_c}{\phi}\frac{\alpha(t)}{\gamma_c}\left(\gamma_D + \gamma_L \frac{\boldsymbol{L}}{\boldsymbol{D}}\right)$$

ex) $\alpha(t) = \frac{\phi M_n(t)}{M_u}$

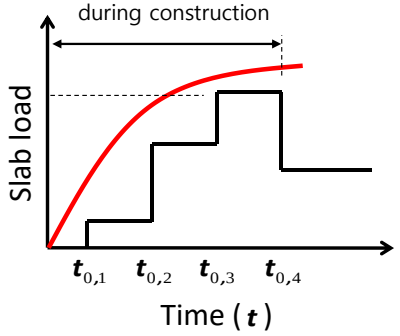
* M_u is the value according to $1.2DL + 1.6LL$

Construction collapse due to delayed strength development during construction





Reduction and delay in construction load through construction plan modification

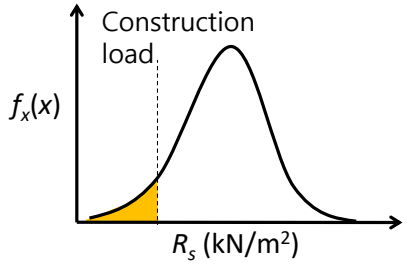


Early strength development of concrete

4. Structural Safety Assessment of Slab

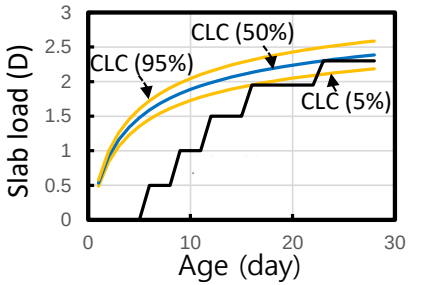
✓ Failure probability

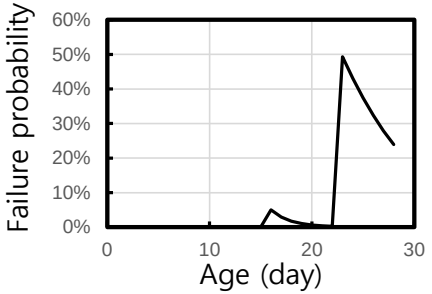
Cumulative distribution addressing construction errors of 1) concrete cover and 2) design models



$$P\left(R_s \le \frac{C_t}{D}\right) = \int_{-\infty}^{C_t/D} f_x(x)$$

$$R_s \sim N(\, m_p(R_S),\ \sigma_p(R_s)^2\,)$$





- Mean and Standard Deviation
  for Calculating Flexural Strength Failure Probability

$$m(\alpha(t)) = \frac{\phi A_s f_y (d - m_d - 0.5a(t))}{M_u} \qquad \sigma(\alpha(t)) = \sqrt{\frac{(\phi A_s f_y)^2 \sigma_d^2}{(M_u)^2}}$$

$$m(R_s) = \frac{\phi_c}{\phi} m(\alpha(t))(1.2 + 1.6\frac{L}{D}) \qquad \sigma(R_s) = \frac{\phi_c}{\phi}\sigma(\alpha(t))(1.2 + 1.6\frac{L}{D})$$

$$m_P(R_s) = m(R_s) \times m_P \qquad \sigma_P(R_s) = \left[\left(\frac{\sigma(R_s)}{m(R_s)}\right)^2 + \left(\frac{\sigma_P}{m_P}\right)^2\right]^{0.5} \times m_P(R_s)$$

- Mean and Standard Deviation
  for Calculating Shear Strength Failure Probability

$$m_P(R_s) = R_s \times m_P \qquad \sigma_P(R_s) = R_s \times \sigma_p$$

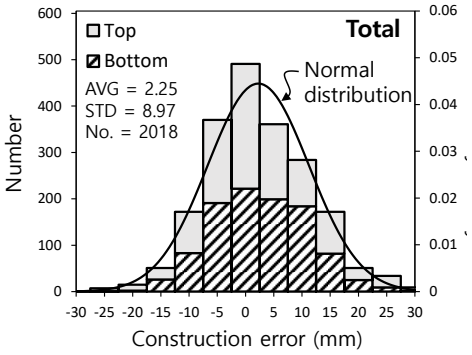


Table 8—Statistical parameters of professional factor

Item	λ	V
Beam, flexure	1.02	0.06
Beam, shear	1.075	0.10
Slab	1.02	0.06
Column, tied	1.00	0.08
Column, spiral	1.05	0.06
Plain concrete	1.02	0.06

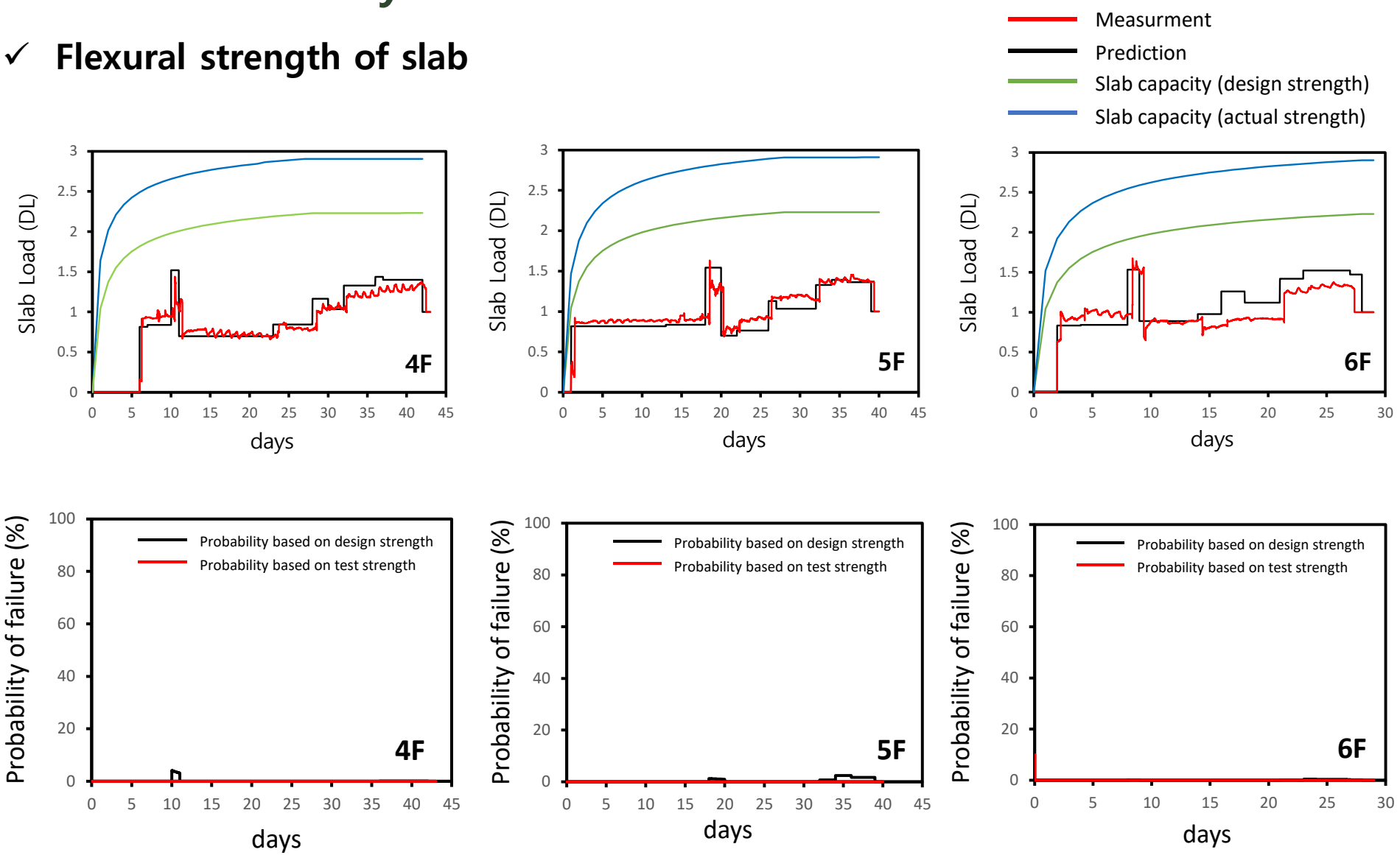
Calibration of Design Code for Buildings (ACI318): Part1 – Statistical Models for Resistance
Anderzej S. Nowakv and Maria M. Szerszen

✓ Consideration Variables
for Flexural Strength Failure Probability
- Construction Error in Cover Thickness $(m_d = 2.25,\ \sigma_d = 8.97)$
- Error in Experiment/Prediction $(m_p = 1.02,\ \sigma_p = 0.06)$

✓ Consideration Variables
for Shear Strength Failure Probability
- Error in Experiment/Prediction $(m_p = 1.43,\ \sigma_p = 0.246)$

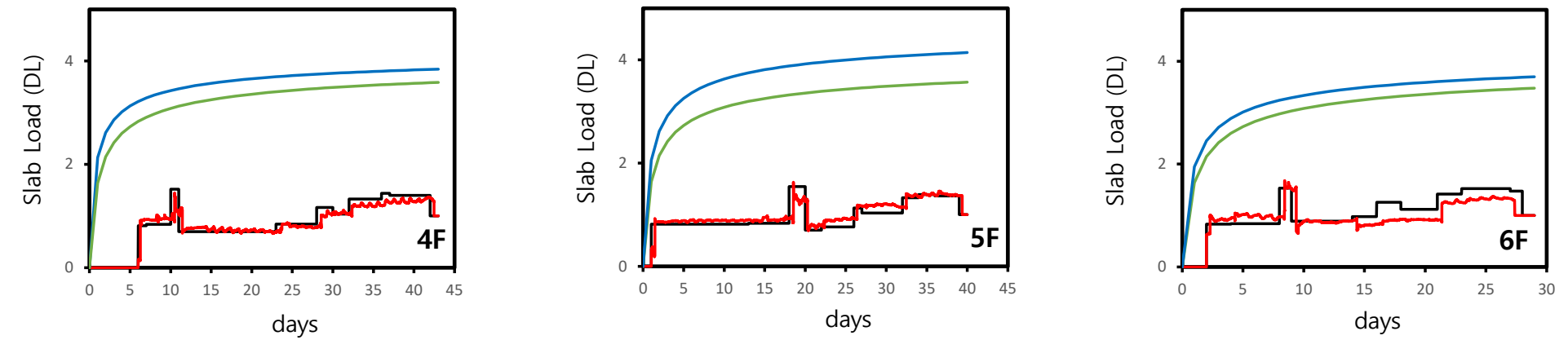
4. Structural Safety Assessment of Slab

✓ Flexural strength of slab

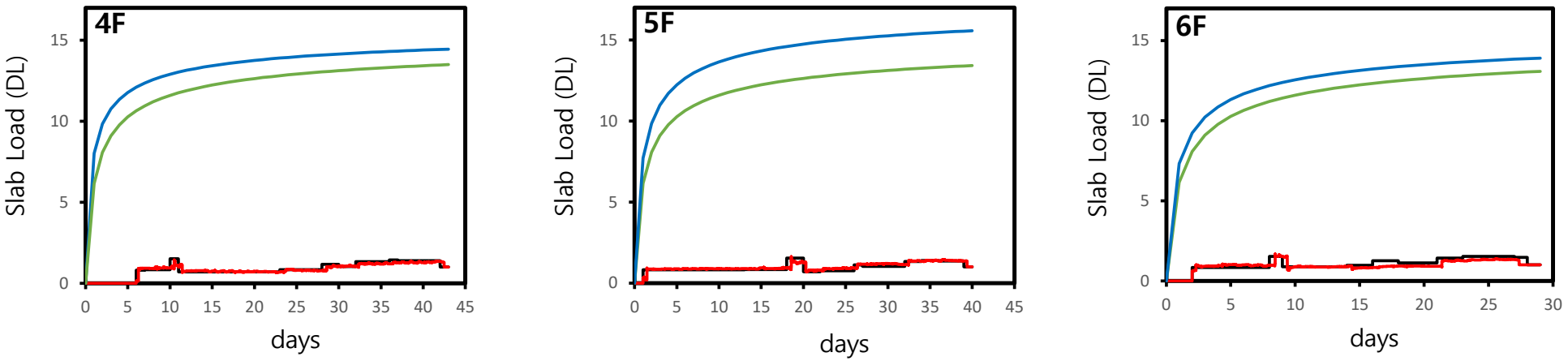


4. Structural Safety Assessment of Slab

✓ Cracking resistance of slab

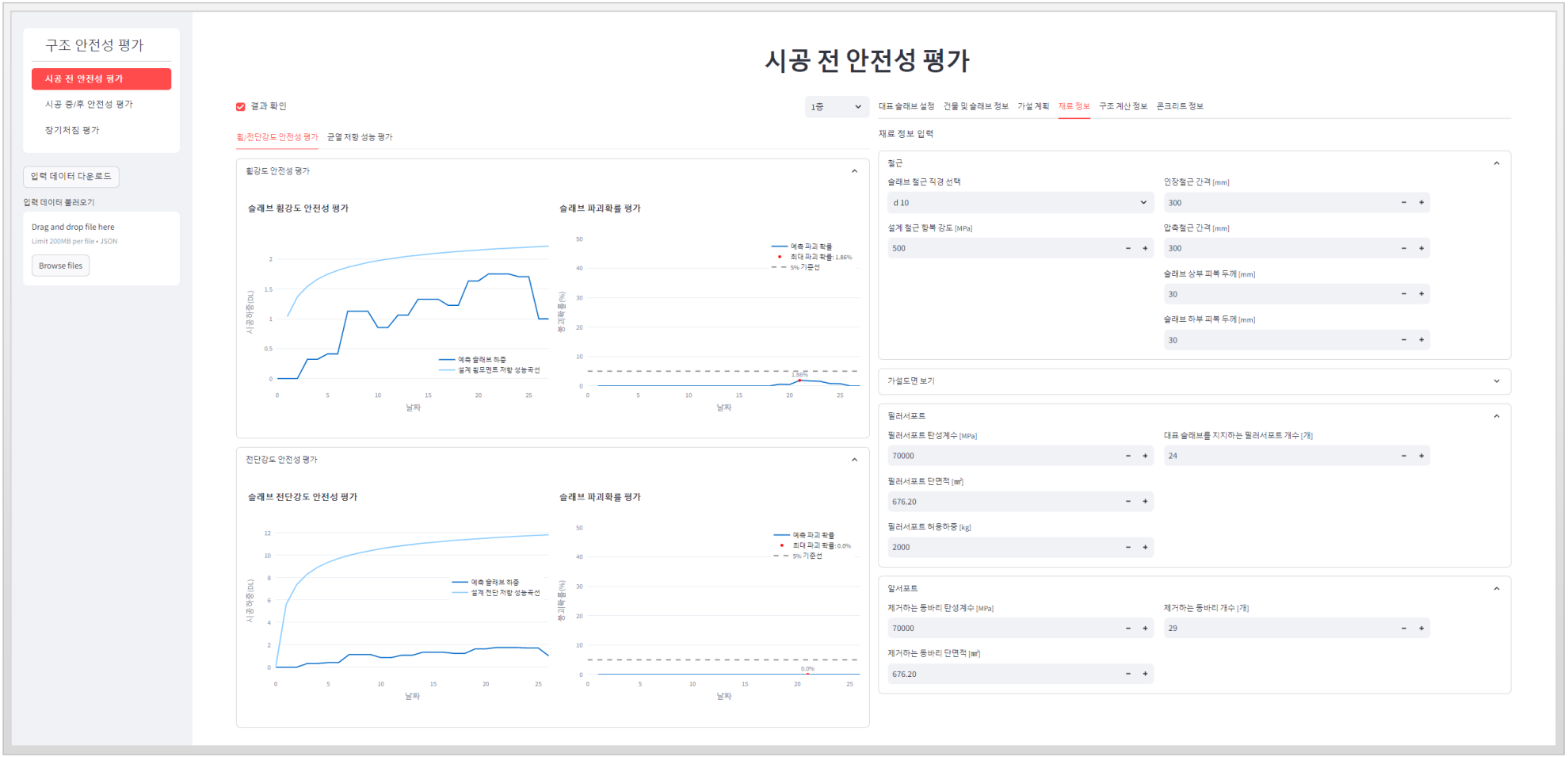


✓ Shear strength of slab



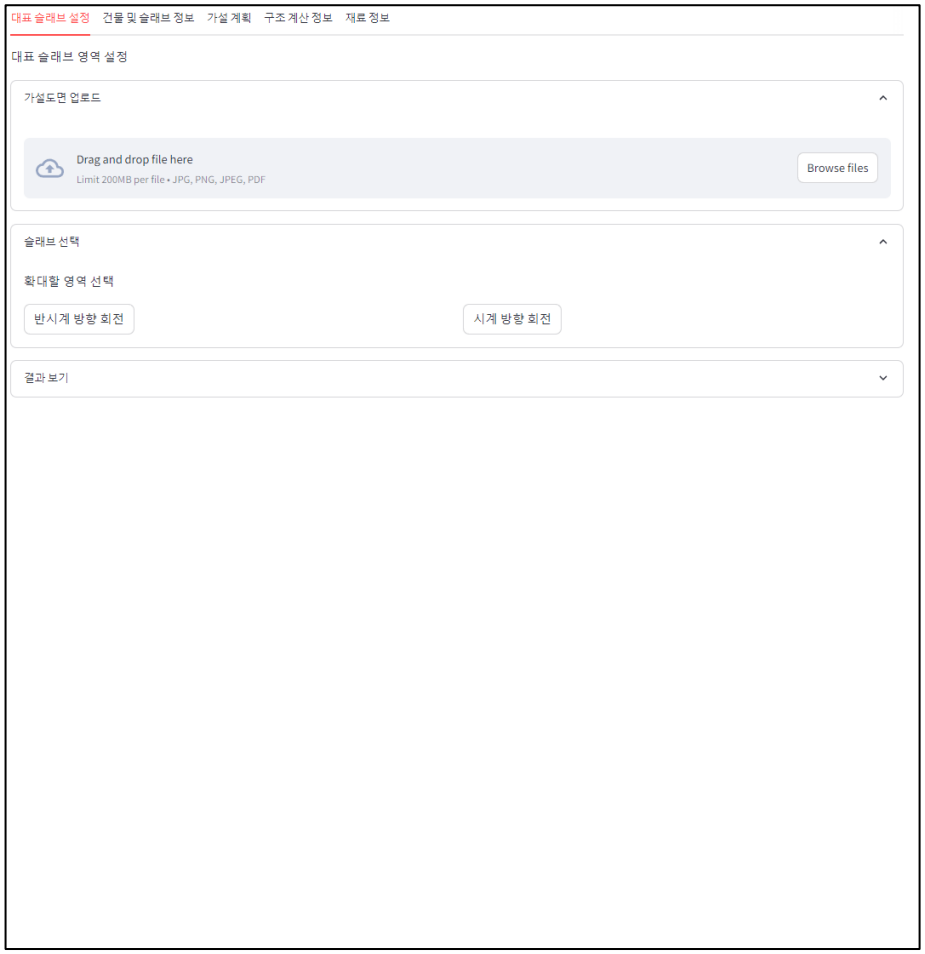
5. Structural Safety Assessment Software

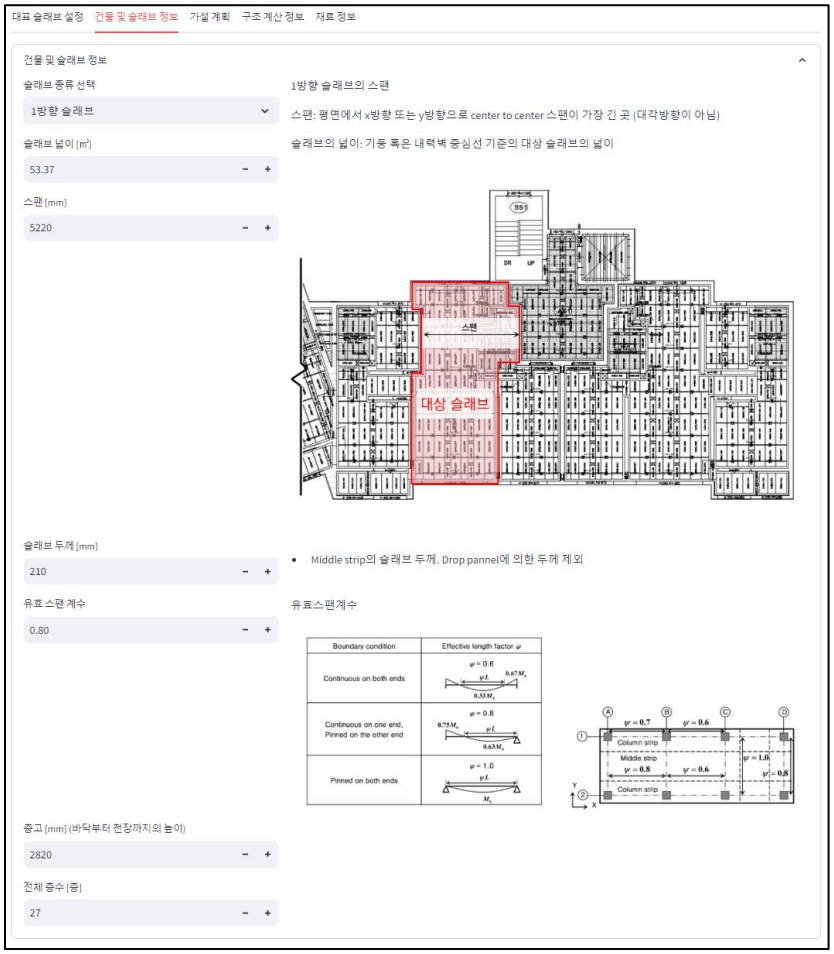
✓ Pre-Construction Safety Assessment



5. Structural Safety Assessment Software

✓ Pre-Construction Safety Assessment

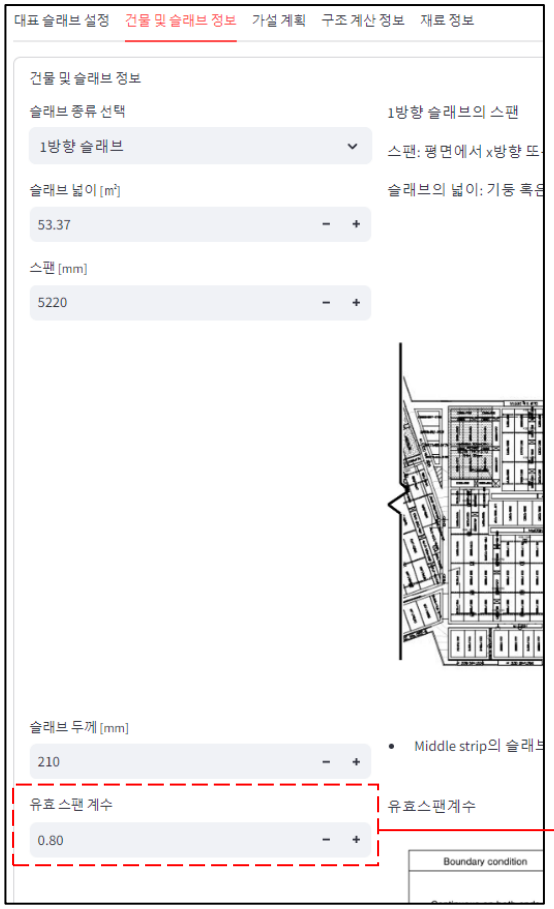




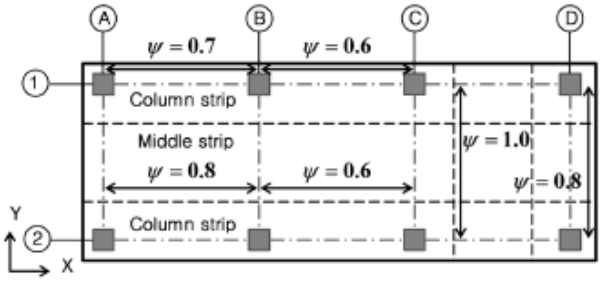
5. Structural Safety Assessment Software

✓ Pre-Construction Safety Assessment

- Determination of Effective Span



Boundary condition	Effective length factor ψ
Continuous on both ends	$\psi = 0.6$, ψL, $0.67M_0$, $0.33M_0$
Continuous on one end, Pinned on the other end	$\psi = 0.8$, $0.75M_0$, ψL, $0.63M_0$
Pinned on both ends	$\psi = 1.0$, ψL, M_0



Determination of Effective Span

→ $L_{eff} = \psi \cdot L$

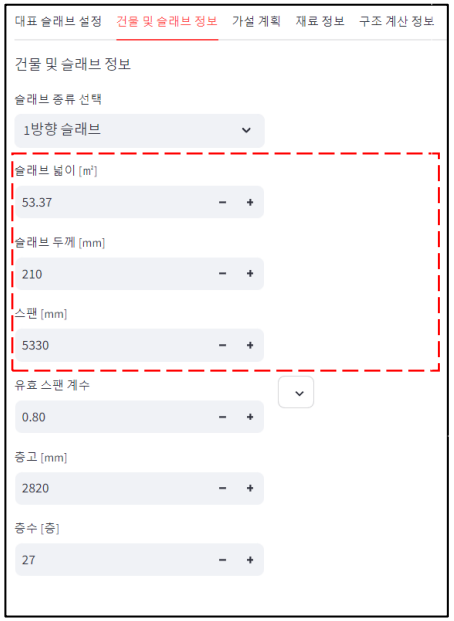
5. Structural Safety Assessment Software

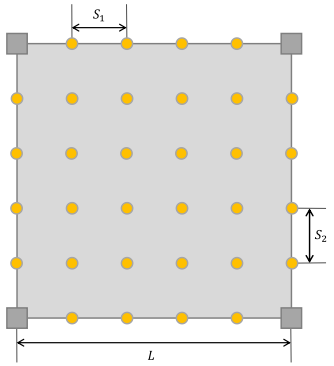
✓ Pre-Construction Safety Assessment

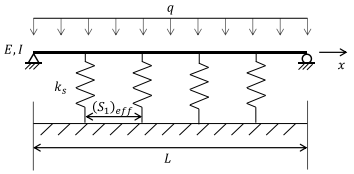
5. Structural Safety Assessment Software

✓ Pre-Construction Safety Assessment

- Shoring stiffness for a single floor







✓ Effective supporting area

→ $A_{eff} = \frac{A_{slab}}{n_{sh}}$

✓ Effective Shoring Spacing

→ $(S_1)_{eff} = \sqrt{A_{eff}}$

✓ Stiffness of a Single Spring

→ $(k_s)_{eff} = \frac{A_s \cdot E_s}{(S_1)_{eff} \cdot H}$

$$v = \frac{q}{k_s}\left[1 - \frac{2\sin\frac{\beta L}{2}\cdot\sinh\frac{\beta L}{2}}{\cos\beta L+\cosh\beta L}\cdot\sin\beta x\cdot\sinh\beta x - \frac{2\cos\frac{\beta L}{2}\cdot\cosh\frac{\beta L}{2}}{\sin\beta L+\sinh\beta L}\cdot\cos\beta x\cdot\cosh\beta x\right],$$

$$\beta = \sqrt[4]{\frac{k_s}{4EI}}$$

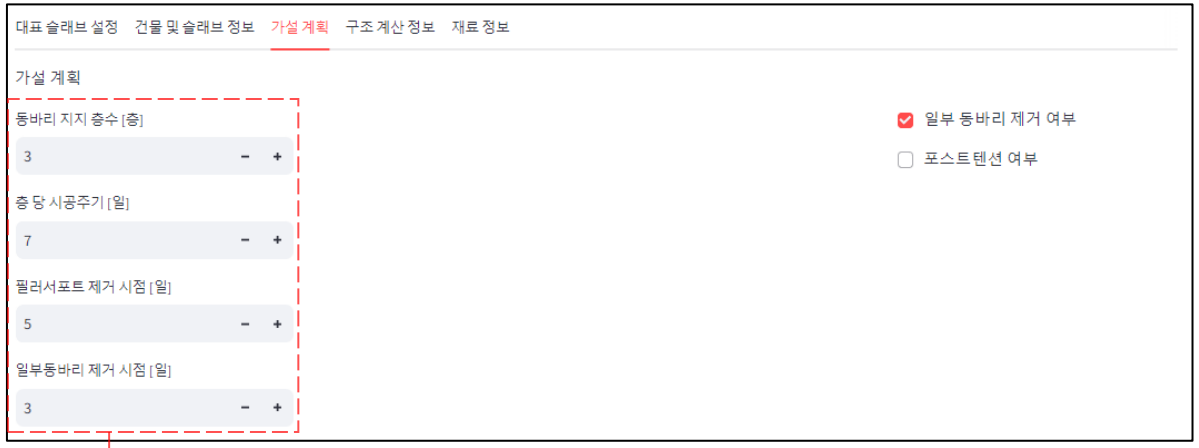
$$L_{sp} = S_1 k_s \sum_{i=1}^{n_s} v_i, \qquad L_{sl} = qL - L_{sp}$$

$$K = \frac{L_{sl}}{L_{sp}} \quad \rightarrow \quad K = \frac{L_{sl}}{L_{sp}} = \frac{k_{sl}}{k_{sp}} \quad \rightarrow \quad k_{sp} = \frac{k_{sl}}{K} = \frac{E(t)I}{K}$$

5. Structural Safety Assessment Software

✓ Pre-Construction Safety Assessment

- Construction schedule



Construction Schedule Generation Based on the 1st Floor Slab Casting Date

✓ Pouring Schedule	✓ Temporary Support Removal Schedule	✓ Regular Support Removal Schedule
1F: day 0	1F: day 10	1F: day 27
2F: day 7	2F: day 17	2F: day 34
3F: day 14	3F: day 24	3F: day 41
4F: day 21	4F: day 31	4F: day 48
⋮	⋮	⋮

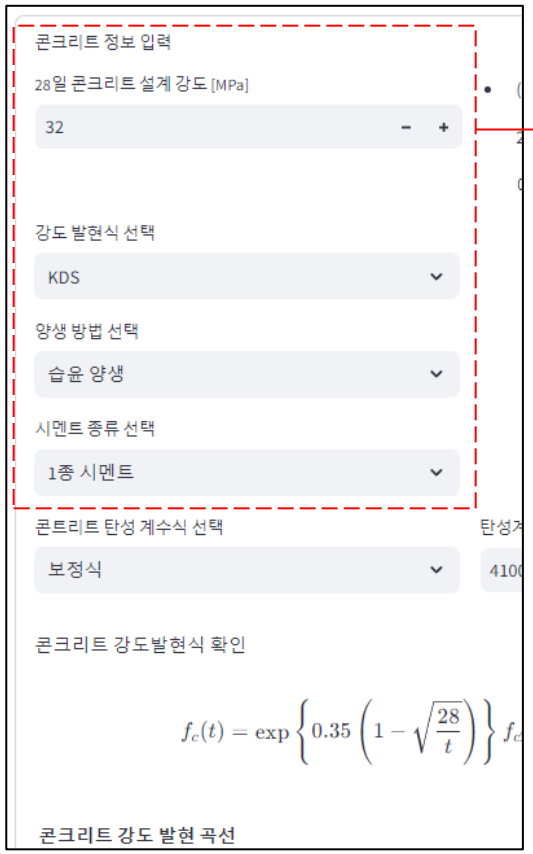
5. Structural Safety Assessment Software

✓ Pre-Construction Safety Assessment

5. Structural Safety Assessment Software

✓ Pre-Construction Safety Assessment

- Concrete strength development



KDS

→ $f_c(t) = \exp\left\{\beta_{sc}\left(1-\sqrt{\frac{28}{t}}\right)\right\} f_{c,28}$

→ Wet Curing

→ Type I : $\beta_{sc} = 0.35$

→ Type II : $\beta_{sc} = 0.40$

→ Type III : $\beta_{sc} = 0.25$

→ Steam Curing

→ Type I : $\beta_{sc} = 0.15$

→ Type II : $\beta_{sc} = 0.40$

→ Type III : $\beta_{sc} = 0.12$

ACI 209

→ $f_c(t) = \frac{t}{\alpha+\beta\cdot t} f_{c,28}$

→ Wet Curing

→ Type I : $\alpha = 4,\ \beta = 0.85$

→ Type II, III : $\alpha = 2.3,\ \beta = 0.92$

→ Steam Curing

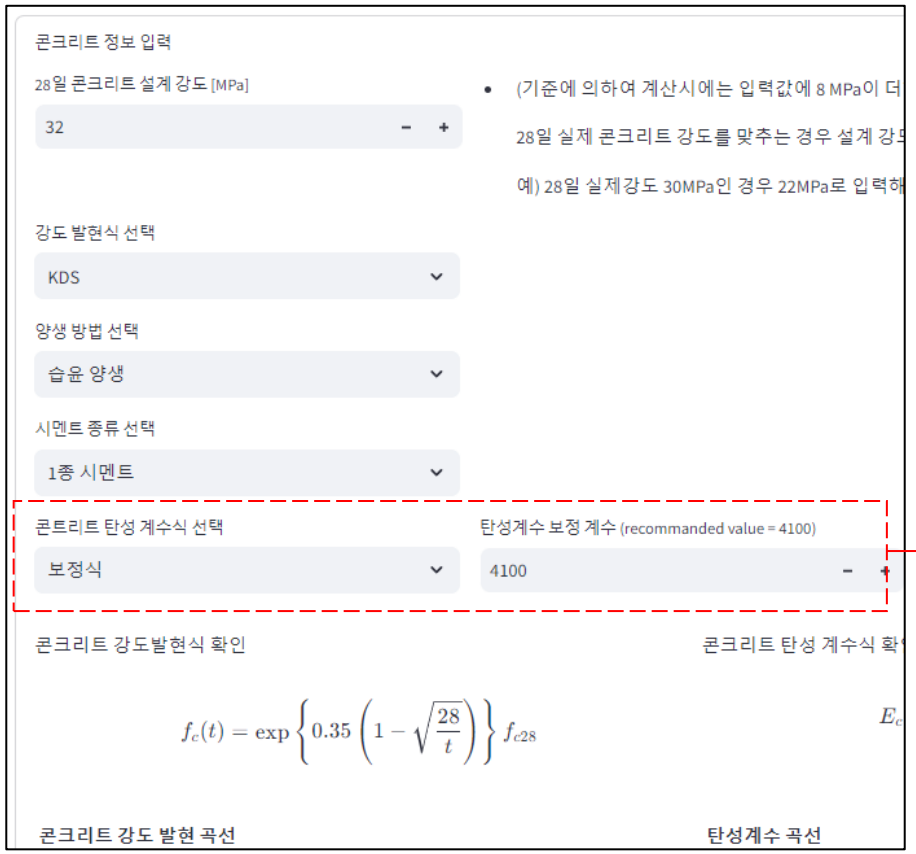
→ Type I : $\alpha = 1,\ \beta = 0.95$

→ Type II, III : $\alpha = 0.7,\ \beta = 0.98$

5. Structural Safety Assessment Software

✓ Pre-Construction Safety Assessment

- Elastic modulus of concrete



KDS & CEB-FIP 1990

$\rightarrow E_c = 8500 * \sqrt[3]{f_c(t)}$

ACI 209

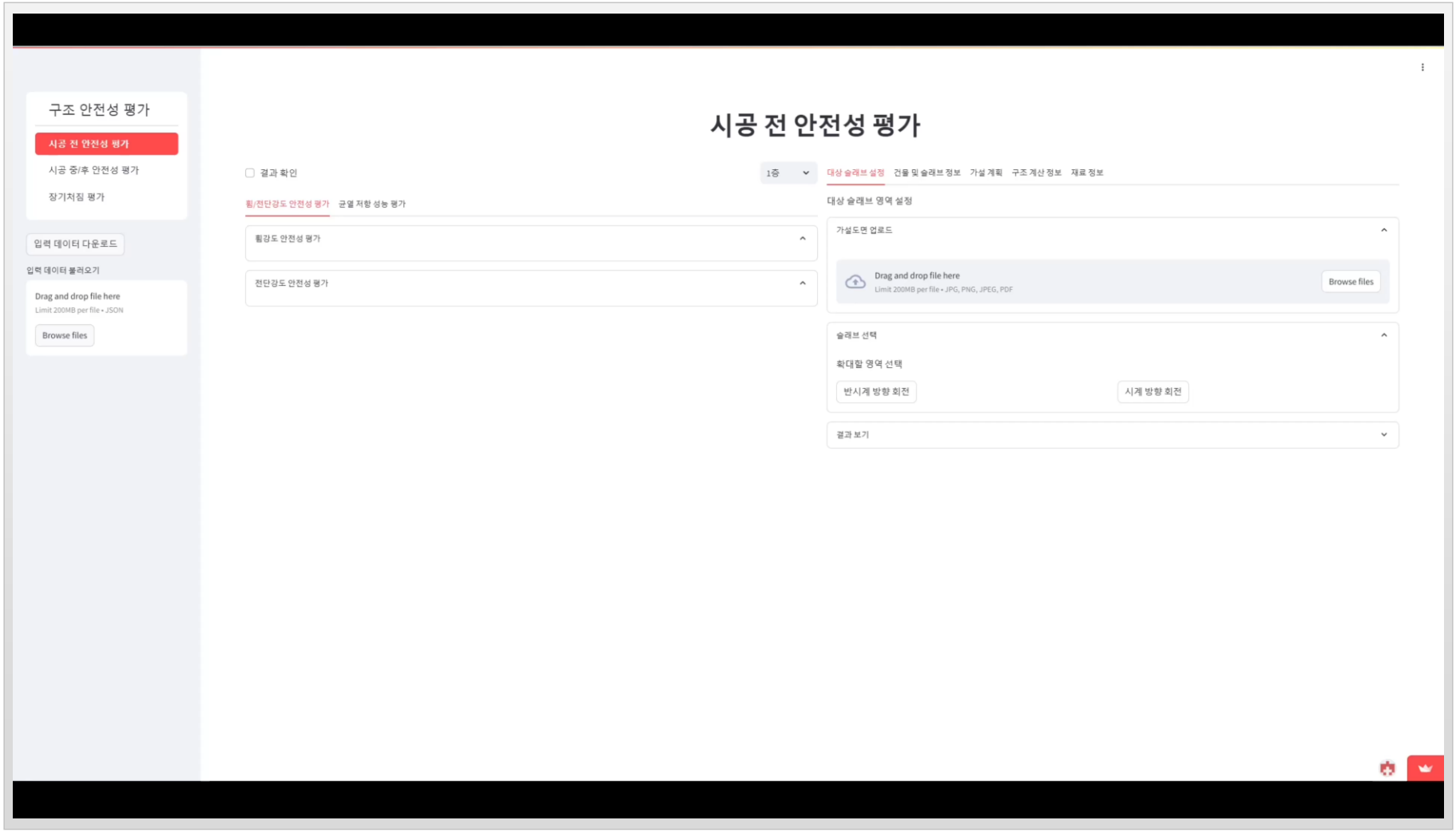
$\rightarrow E_c = 4700 * \sqrt{f_c(t)}$

Modified

$\rightarrow E_c = a_E * \sqrt{f_c(t)}$

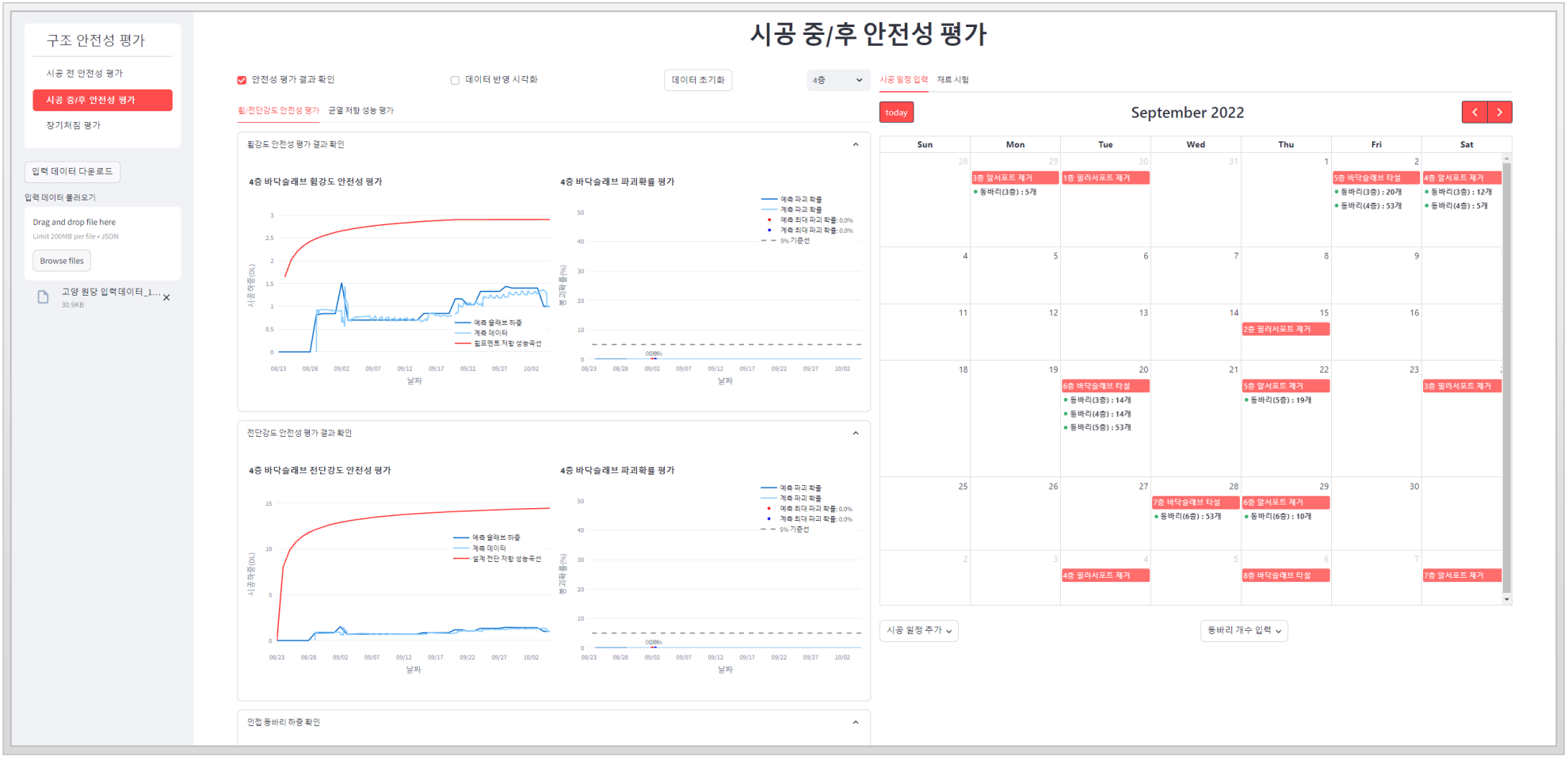
5. Structural Safety Assessment Software

✓ Pre-Construction Safety Assessment



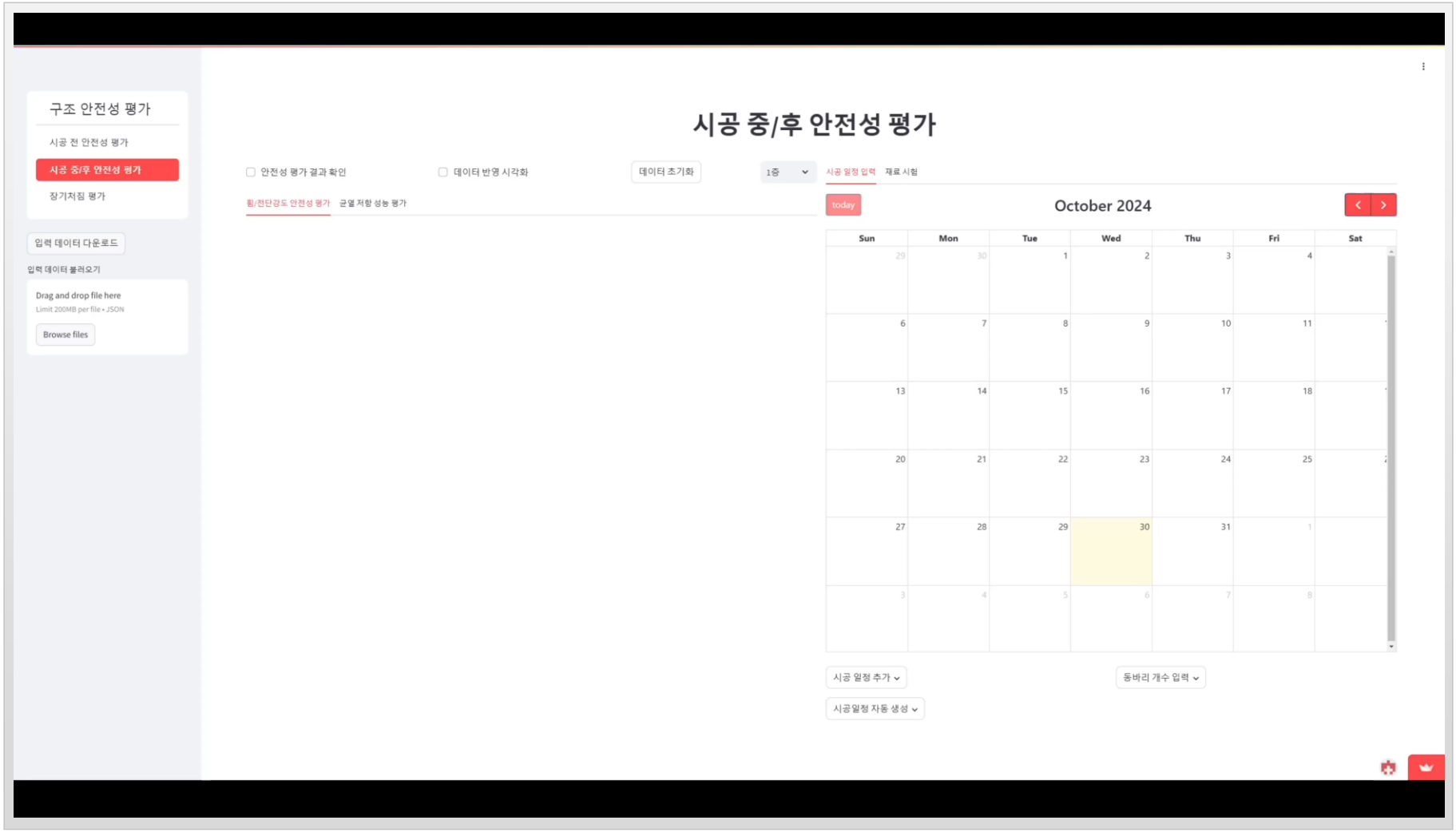
5. Structural Safety Assessment Software

✓ During and Post-Construction Safety Assessment



5. Structural Safety Assessment Software

✓ During and Post-Construction Safety Assessment



Conclusions

1. Construction load : at early-aged slab concrete

2. Critical to slab cracking & load resistance

3. Prediction model of construction load

4. Prediction of failure probability of slab under construction

5. Structural Safety Assessment Software