Modeling of Deformation Behavior of Concrete under Fatigue Loading

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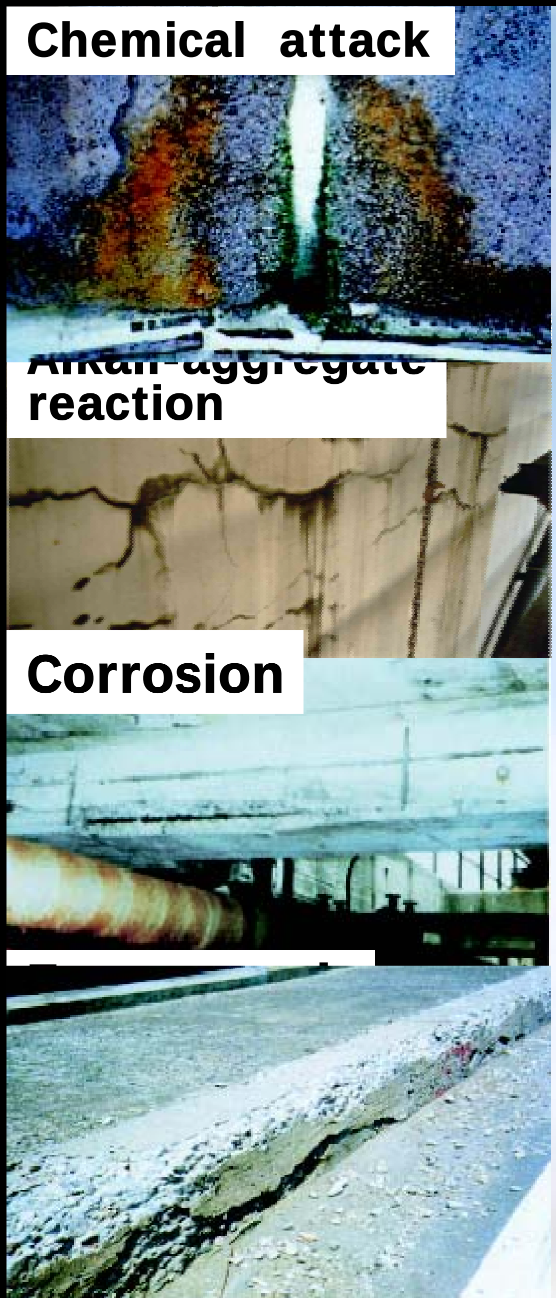
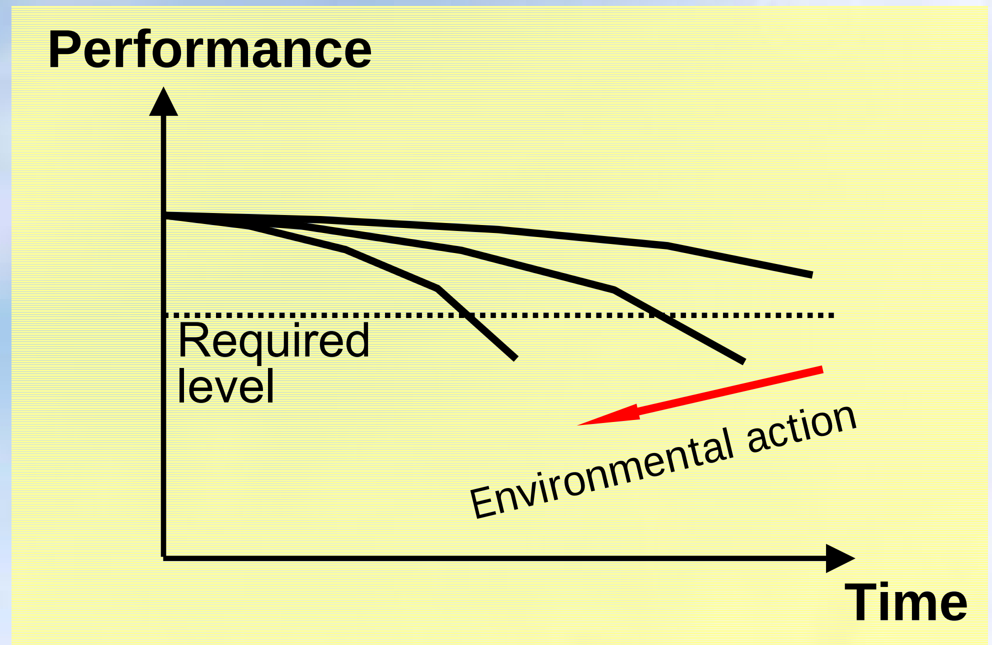
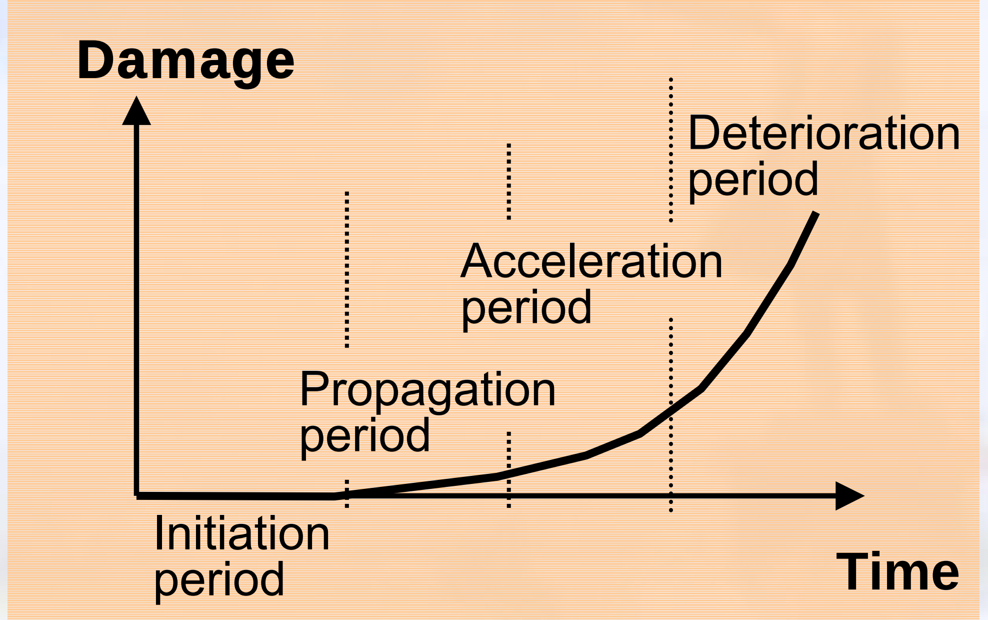
COE Workshop

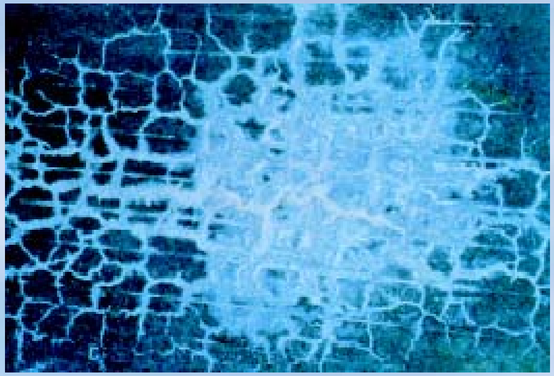
Deterioration Mechanism and Performance of Structures







Fatigue -one of the major deterioration mechanism

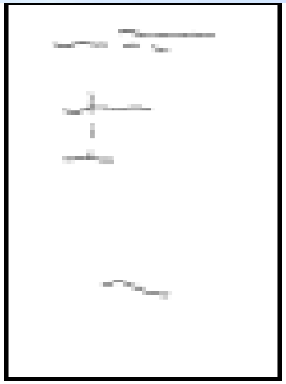


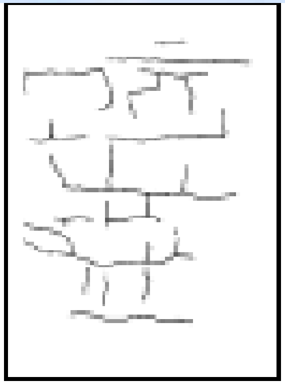
Initiation period

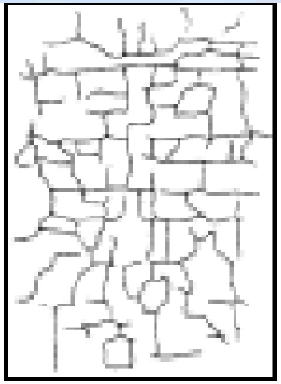
Propagation period

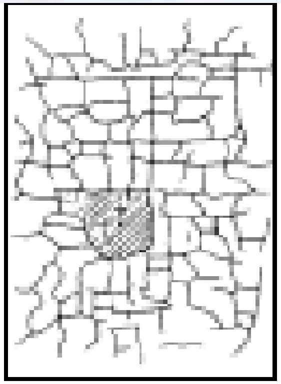
Acceleration period

Deterioration period









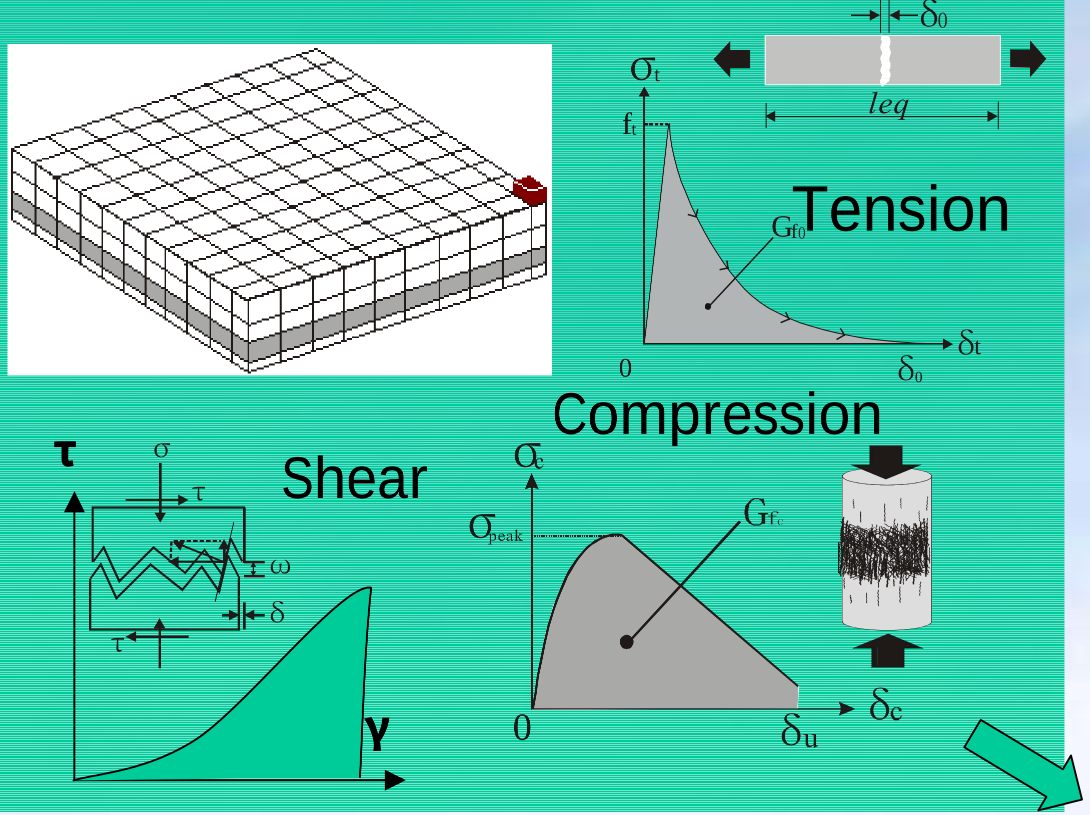
Flexural cracking

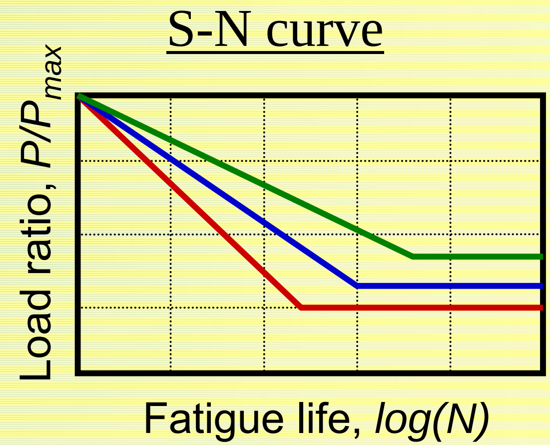
Hexagonal cracking pattern

Punching failure

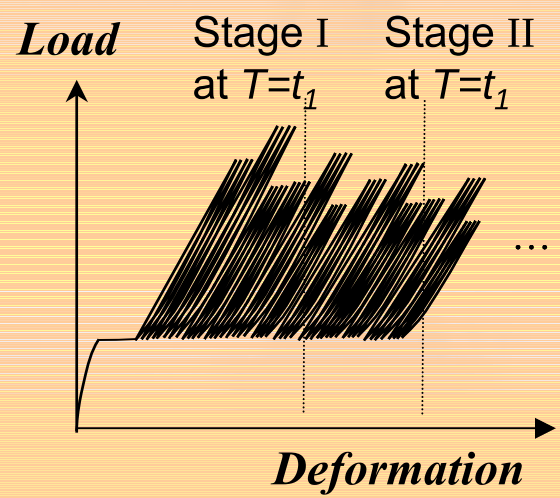
Necessity of Advanced Prediction Method

Shear Capacity Verification using FE Analysis





Damage Procedure
Fatigue life prediction



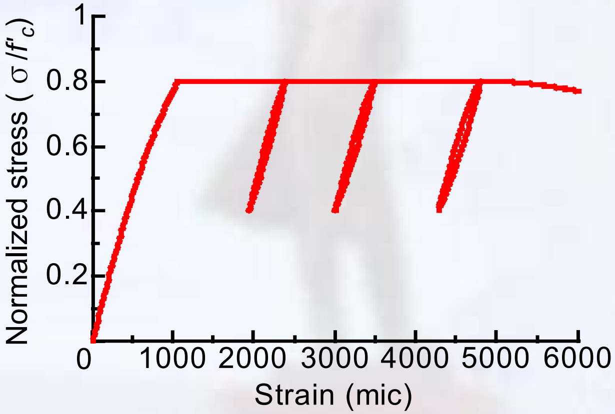
Outline of Study

Experiments for understanding stiffness degradation and strain development under compressive sustained and cyclic loading

Elasto-plastic and fracture (EPF) model proposed by prof.Maekawa

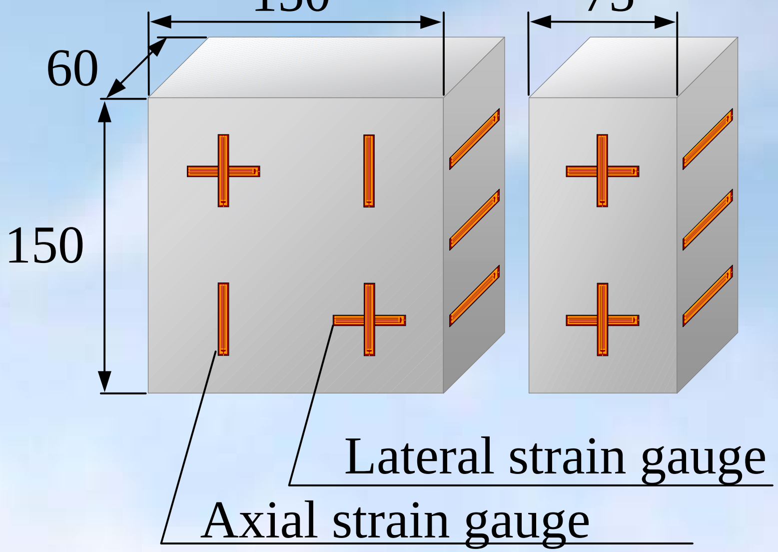
Modeling of fatigue behavior

- Sustained and fatigue
- Stress-strain curve and fatigue life
- Humidity and temperature



Outline of Experiment

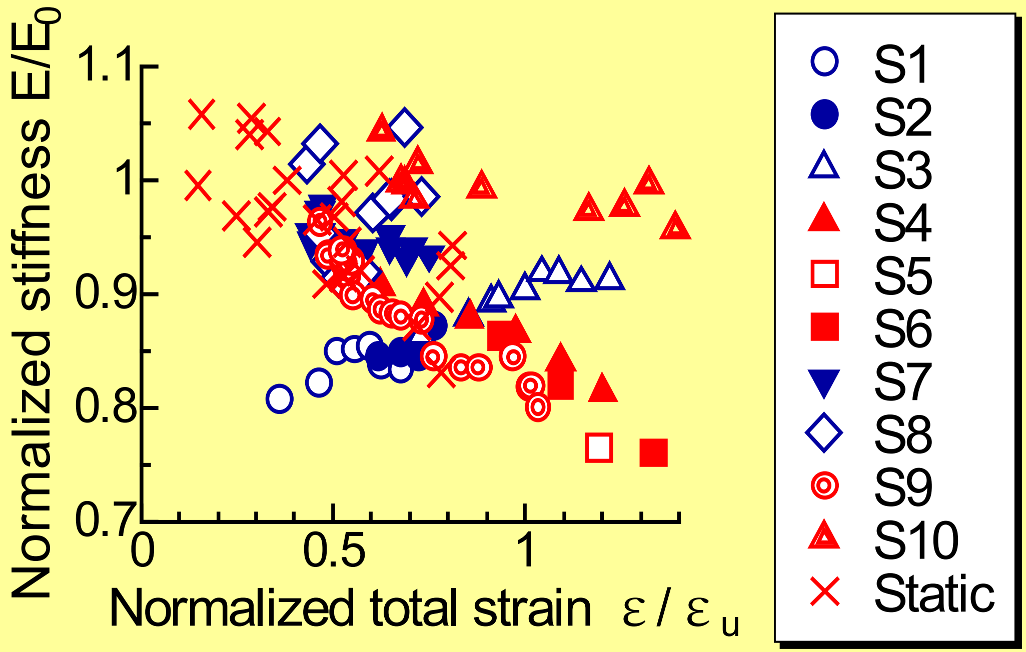
Specimen (unit: mm)

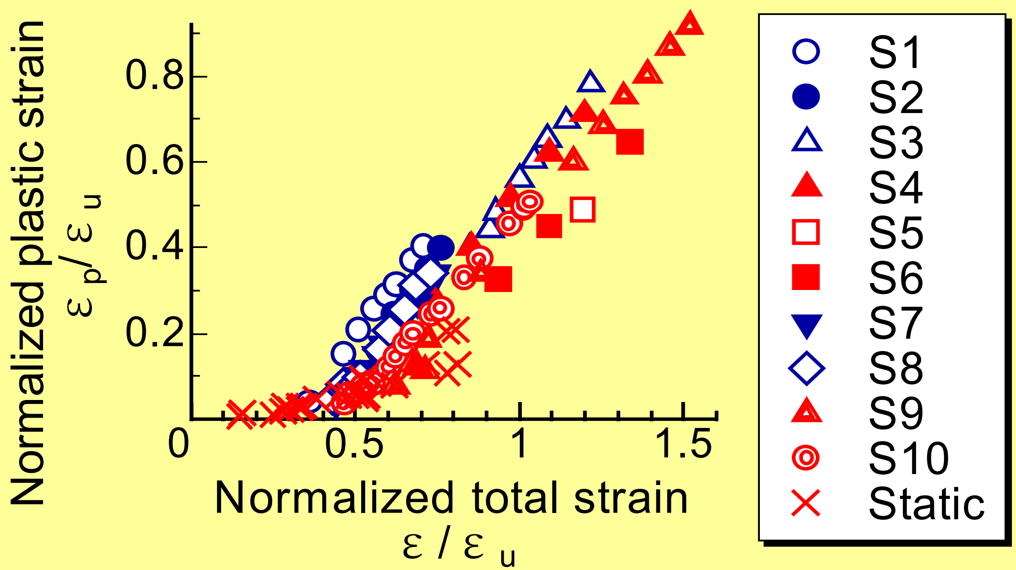


No.	Max stress ratio (%)	Min stress ratio (%)	
S1	57	57	Sustained loading
S2	62	62	
S3	71	71	
S4	80	80	
S5	90	90	
S6	90	90	
S7	60	20	Cyclic loading
S8	60	40	
S9	70	15	
S10	70	30	

Mix proportion	W/C=60, s/a=41% C=266.7 (kg/m³) W=160.0 (kg/m³)

Experimental Results and Discussion (1)





Stiffness reduction

High stress :

➡ decrease

Low stress :

➡ contact

Plastic strain

Lower stress :

➡ Higher increment

Experimental Results and Discussion (2)

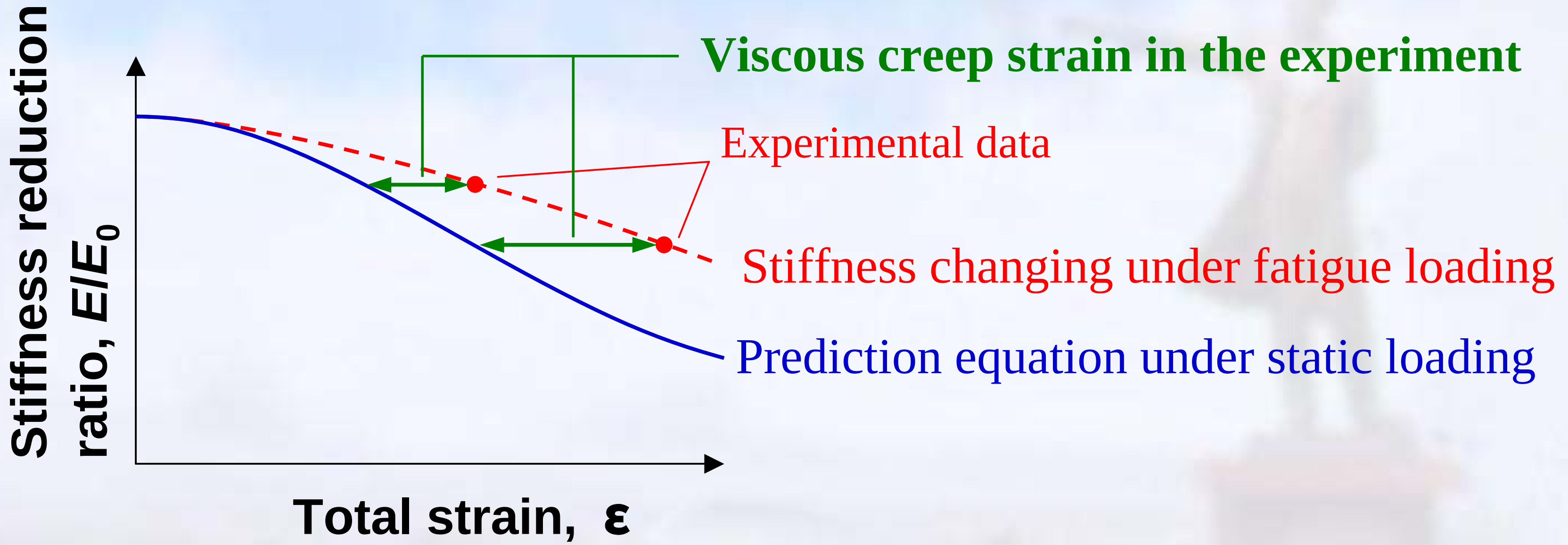
Viscous creep strain

Total strain = Cracking strain + Viscous creep strain

(Crack propagation) (Consolidation of mortal)

It reduces concrete stiffness

It does not affect concrete stiffness



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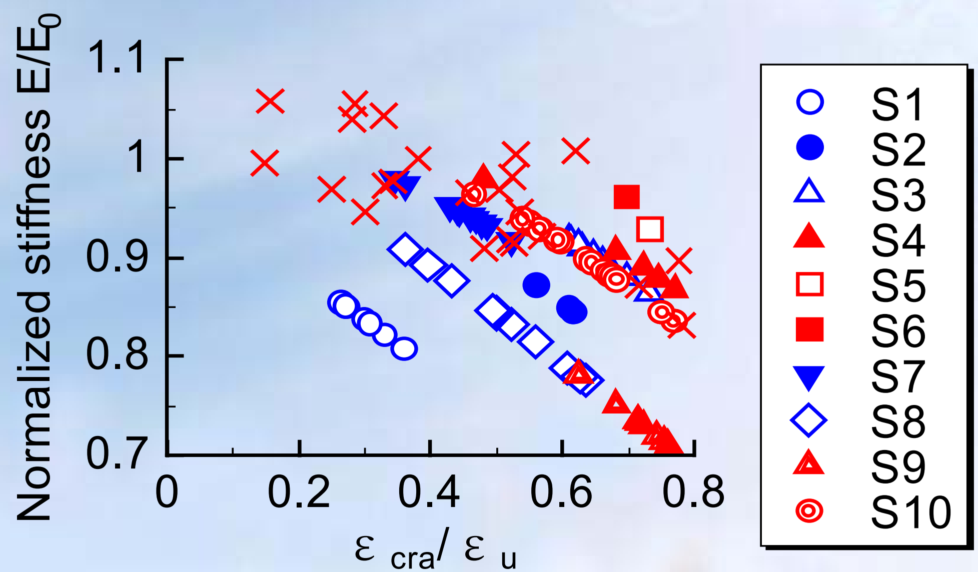
Experimental Results and Discussion (3)

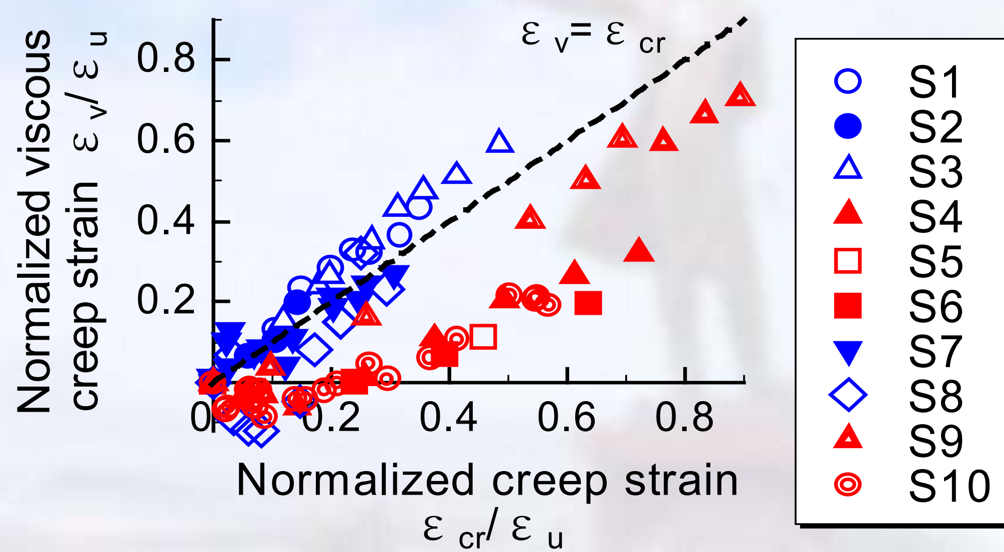
3. Stiffness and cracking strain

✓ Stiffness reduction can be expressed as cracking strain, which is deducted viscous creep strain from total strain.



4. Viscous creep strain

✓ Lower stress condition, ratio of viscous creep strain is higher.



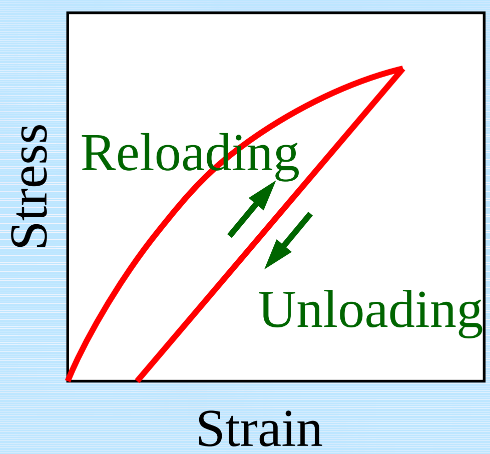
MODELING(1)

Elasto-plastic fracture (EPF) model

$$\frac{\sigma}{f'_c} = E_0 K_0 \frac{\varepsilon_e}{\varepsilon'_u} = E_0 K_0 \frac{\varepsilon - \varepsilon_p}{\varepsilon'_u}$$

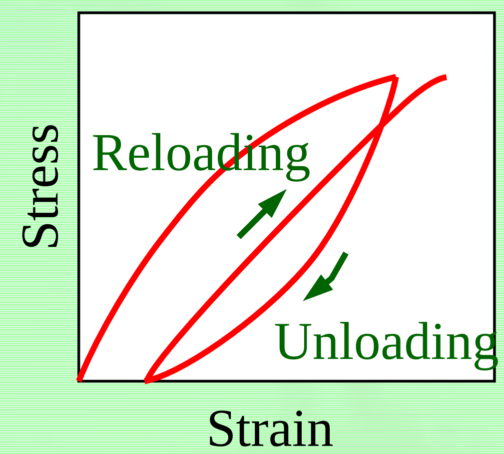
Fracture parameter $K_0 = \exp\left[-0.73\frac{\varepsilon_t}{\varepsilon'_u}\left\{1-\exp\left(-1.25\frac{\varepsilon_t}{\varepsilon'_u}\right)\right\}\right]$

Plastic strain $\varepsilon_p = \frac{\varepsilon_t}{\varepsilon'_u} - \frac{20}{7}\left[1-\exp\left(-0.35\frac{\varepsilon_t}{\varepsilon'_u}\right)\right]$



Time Effect

Fatigue model



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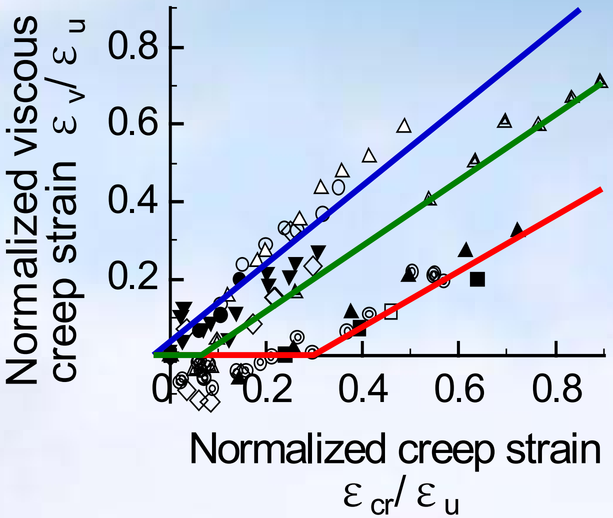
MODELING(2)

1. Fracture parameter under fatigue loading

It be expressed as cracking strain, $\varepsilon_{cra}=\varepsilon-\varepsilon_v$ (ε_v: viscous creep strain)

Viscous creep strain equation (bi-liner model)



When $S_{max}<0.12R+0.6$

$\varepsilon_v=\varepsilon_{cr}$

When $S_{max}>0.12R+0.6$

When $\varepsilon_{cr}<l$

$\varepsilon_v=0$

When $\varepsilon_{cr}>l$

$\varepsilon_v=a(\varepsilon_{cr}-l)$

Where, $l=20(25S_{max}-3R-15)/187$

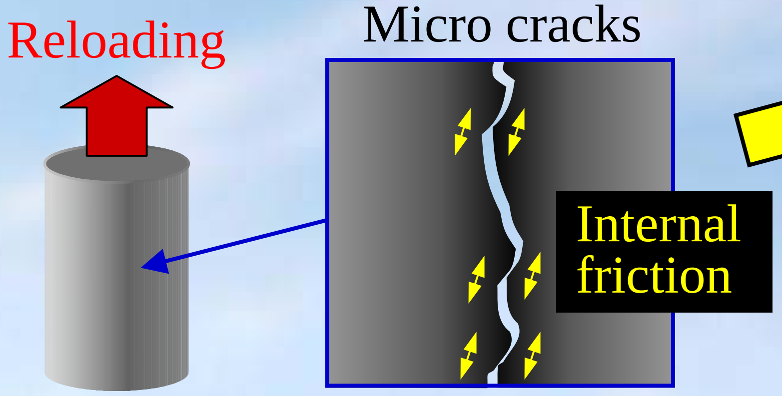
$a=(-625S_{max}+75R+562)/187$

However,
$l<0 \Rightarrow l=0$
$a<0 \Rightarrow a=0$
$a>1 \Rightarrow a=1$

Fracture parameter $K_0=\exp\left[-0.73\frac{\varepsilon_t-\varepsilon_v}{\varepsilon'_u}\left\{1-\exp\left(-1.25\frac{\varepsilon_t-\varepsilon_v}{\varepsilon'_u}\right)\right\}\right]$

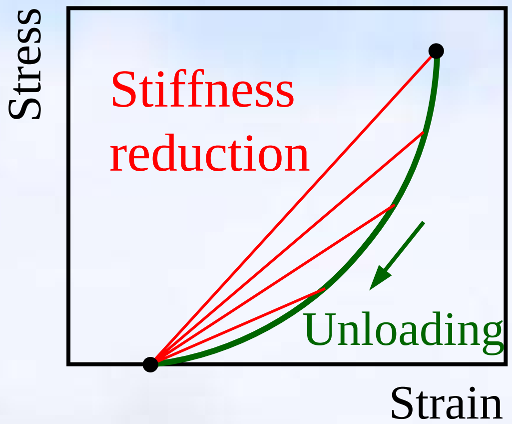
MODELING(3)

2. Stiffness changing in unloading and reloading

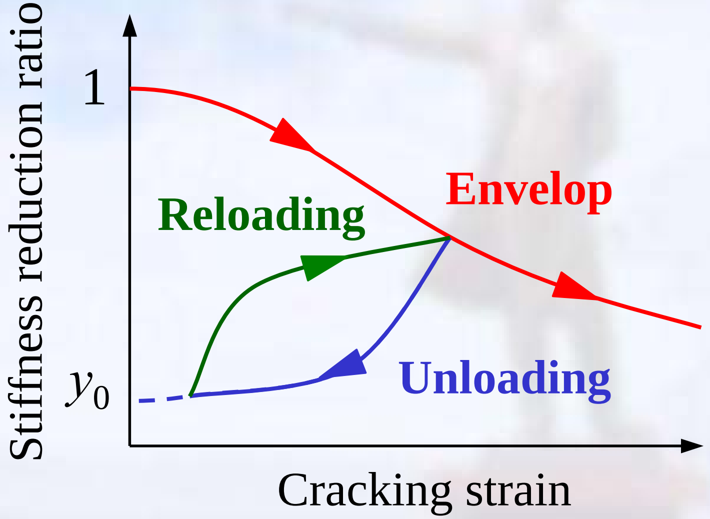


Give nonlinearity to stress-strain curve in unloading

Energy storage is discribed.



Stiffness decreases visually

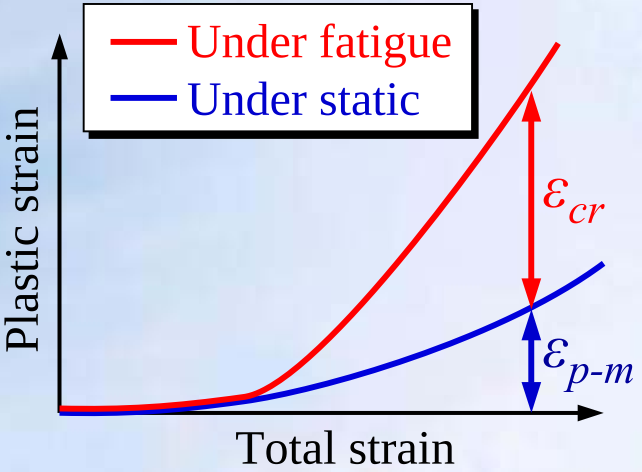


MODELING(4)

3. Plastic strain under fatigue loading

Plastic strain under fatigue loading
= Time-independent plastic strain
+ Time-dependent plastic strain

$\varepsilon_p = \varepsilon_{p\text{-}m}$(Maekawa's equation) +
ε_{cr}(Creep strain prediction equation)



Modified Ayano's equation (creep strain prediction equation)

$$\varepsilon_{cr} = c_y \cdot c_e \cdot \varepsilon(t, t', t_0)$$

$$c_y = \frac{1+R}{2}(1 + 3.87\Delta)$$

$$c_e = \frac{4W(1-h)+350}{587}(0.0133T + 0.733)$$

$$R = \frac{\sigma_{\min}}{\sigma_{\max}}, \quad \Delta = \frac{\sigma_{\max} - \sigma_{\min}}{f'_c}$$

c_y: Coefficient for effect of cyclic loading
c_e: Coefficient for effect of environmental condition
$\varepsilon(t,t',t_0)$: Ayano's creep strain prediction equation

Considered with temperature and humidity
Applicable to fatigue loading

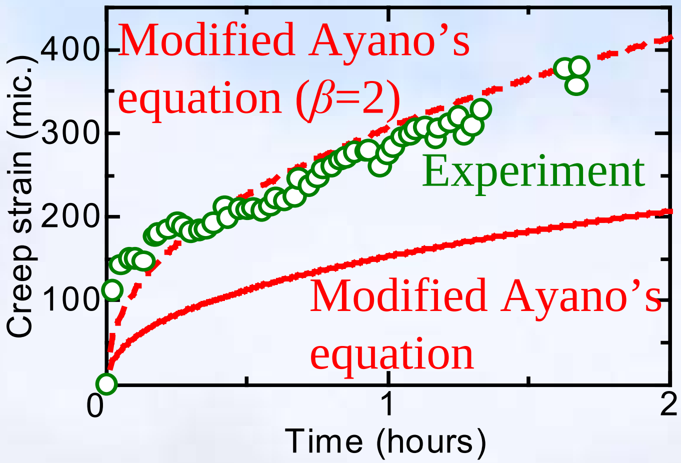
MODELING(5)

Creep strain under high stress

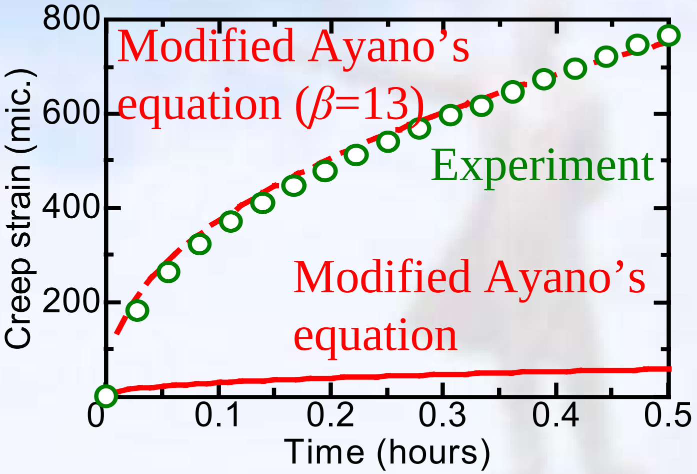
Applicable range of modified Ayano's equation: stress ratio ~50%

It cannot be applied for high stress

Creep strain caused by cracking should be quantified. But it is expressed as multiplying coefficient β which is determined by experimental data.



S9 (S_{max}=65%, S_{min}=0%)



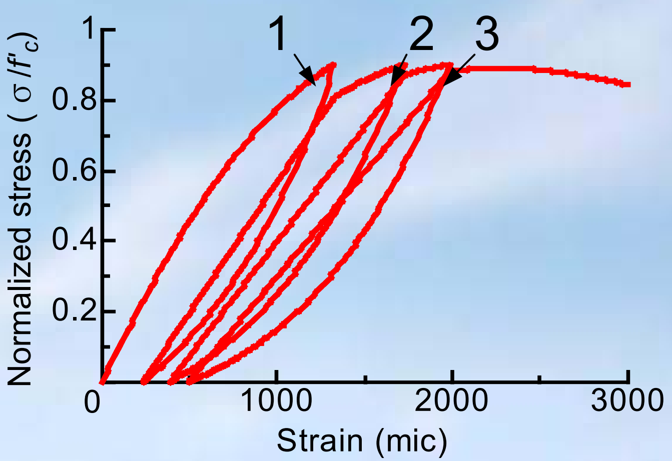
S5 (S=90%)

Parametric Study(1)

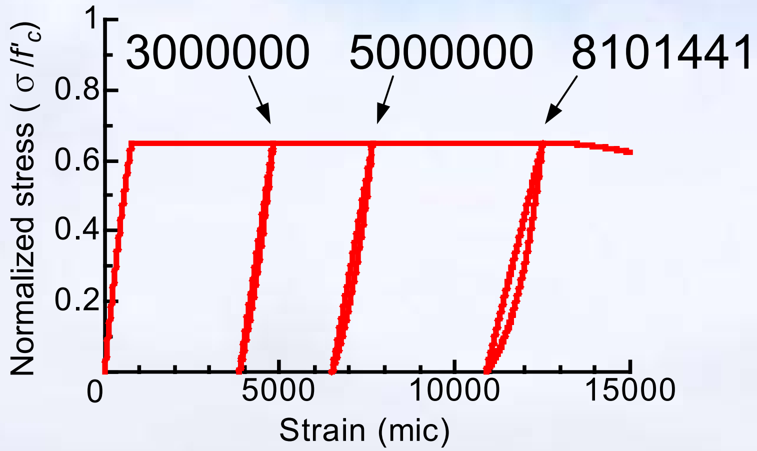
<table>
<tr><th>No.</th><th>Max stress ratio (%)</th><th>Max stress ratio (%)</th><th>Temperature (deg)</th><th>Relative humidity (%)</th><th>Multiplying coefficient β for creep strain prediction equation</th></tr>
<tr><td>S1</td><td rowspan="6">80</td><td rowspan="3">0</td><td>20</td><td>70</td><td rowspan="3">20</td></tr>
<tr><td>S2</td><td>35</td><td>15</td></tr>
<tr><td>S3</td><td>5</td><td>100</td></tr>
<tr><td>S4</td><td>20</td><td rowspan="5">20</td><td rowspan="5">70</td><td>15</td></tr>
<tr><td>S5</td><td>40</td><td>10</td></tr>
<tr><td>S6</td><td>60</td><td>5</td></tr>
<tr><td>S7</td><td>90</td><td rowspan="2">0</td><td>30</td></tr>
<tr><td>S8</td><td>65</td><td>2</td></tr>
</table>

Computed Results(1)

Influence of Maximum Stress

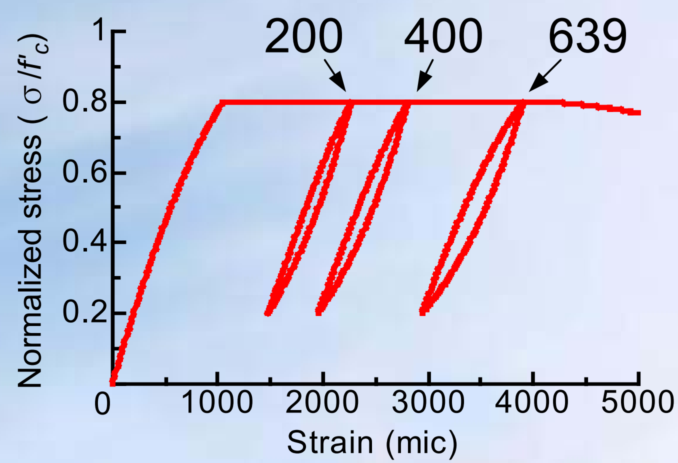


S7 (90%-0%, T=20℃, h=70%)

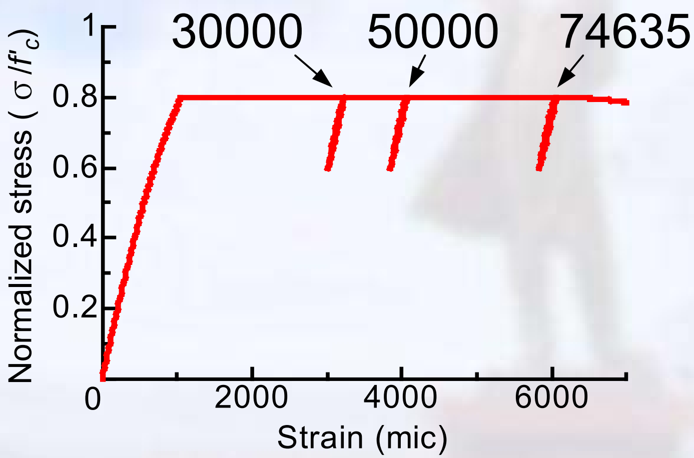


S9 (65%-0%, T=20℃, h=70%)

Influence of Minimum Stress



S4 (80%-20%, T=20deg, h=70%)



S6 (80%-60%, T=20deg, h=70%)

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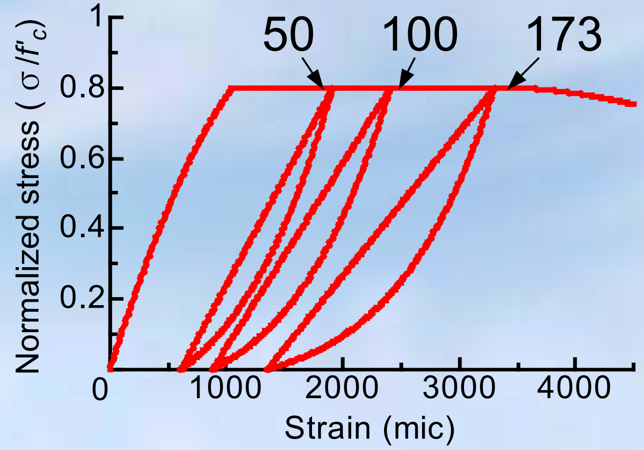
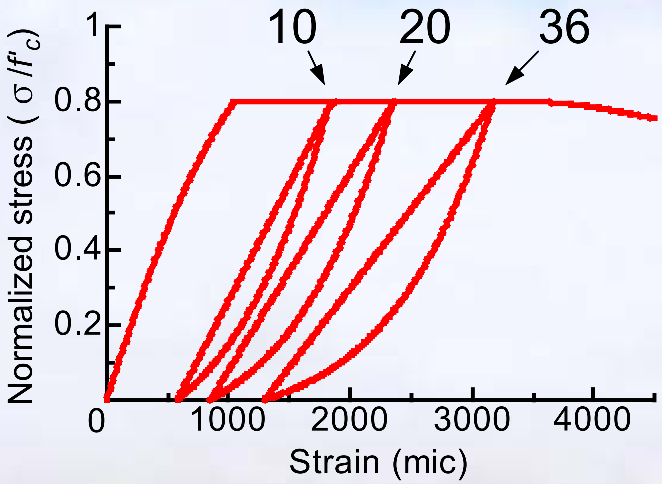
Computed Results (2)

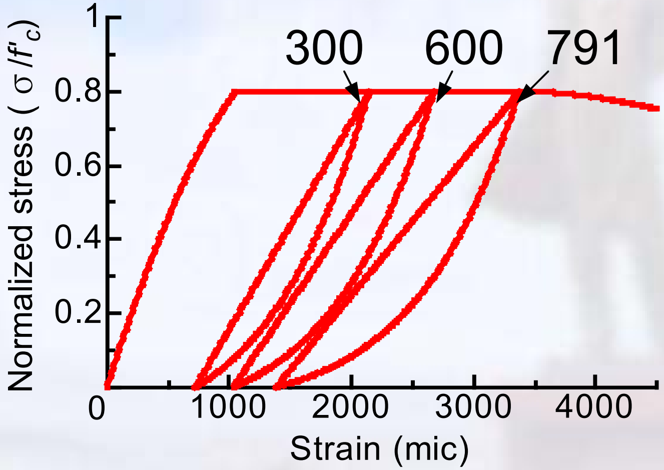
Effect of environmental condition



S1 (80%-0%, T=20deg, h=70%)



S2 (80%-0%, T=35deg, h=15%)

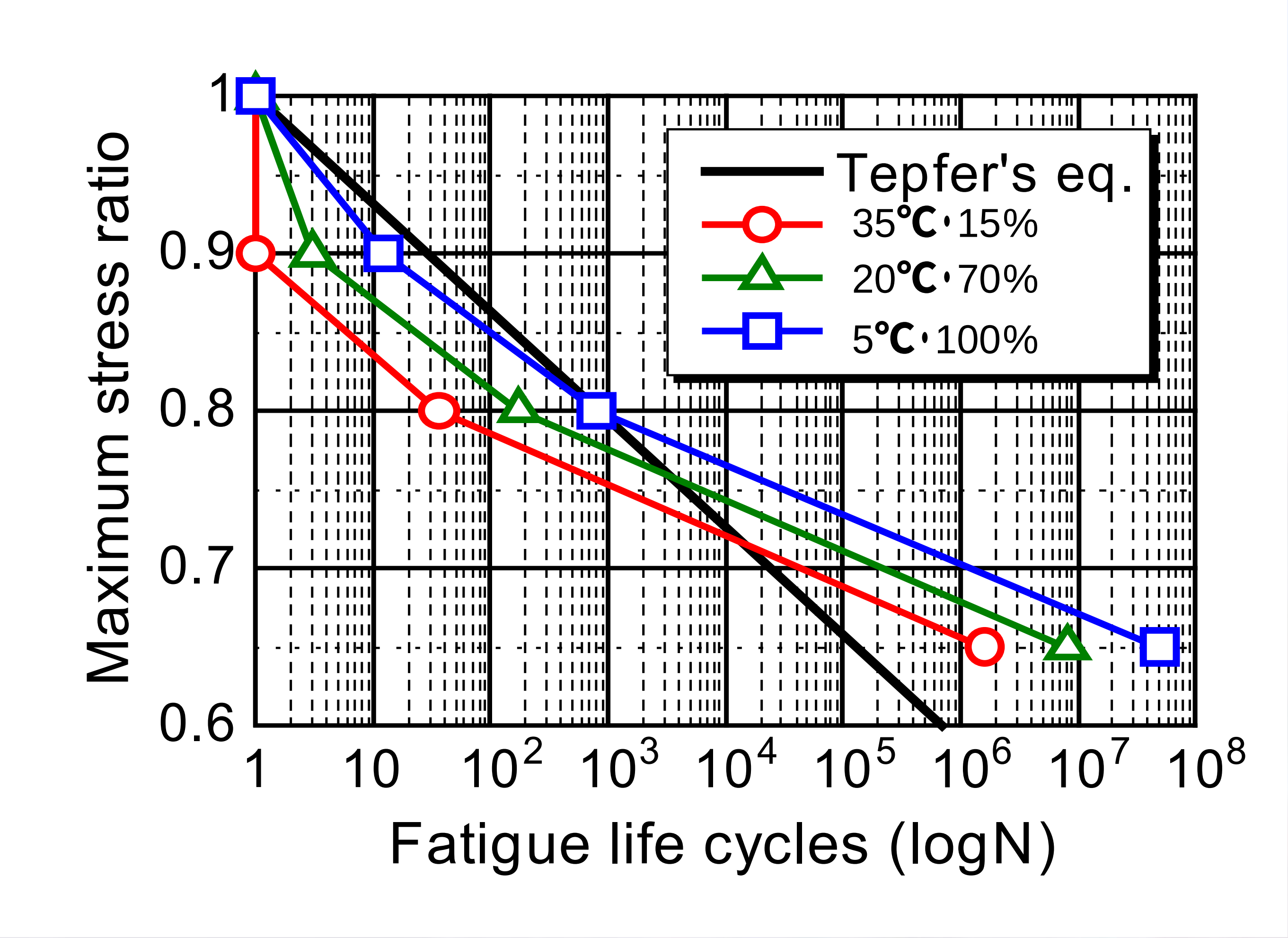


S3 (80%-0%, T=5deg, h=100%)

Fatigue Life

Tepfers's equation

$$\frac{\sigma_{max}}{f'_c} = 1 - 0.0685\left(1 - \frac{\sigma_{min}}{\sigma_{max}}\right)\log_{10} N$$



Conclusion and Future Perspective

Stress – strain curves of concrete under compressive sustained and fatigue loading

/Strain components : Cracking strain
Viscous creep strain
/Stiffness reduction : Cracking strain

Parametric Study using the Model

/Fatigue life influenced by humidity and temperature