TAIWAN TECH

高強度鋼筋混凝土梁之裂縫發展與控制

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Life-Cycle of Structure Engineering

2015/12/11

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Content

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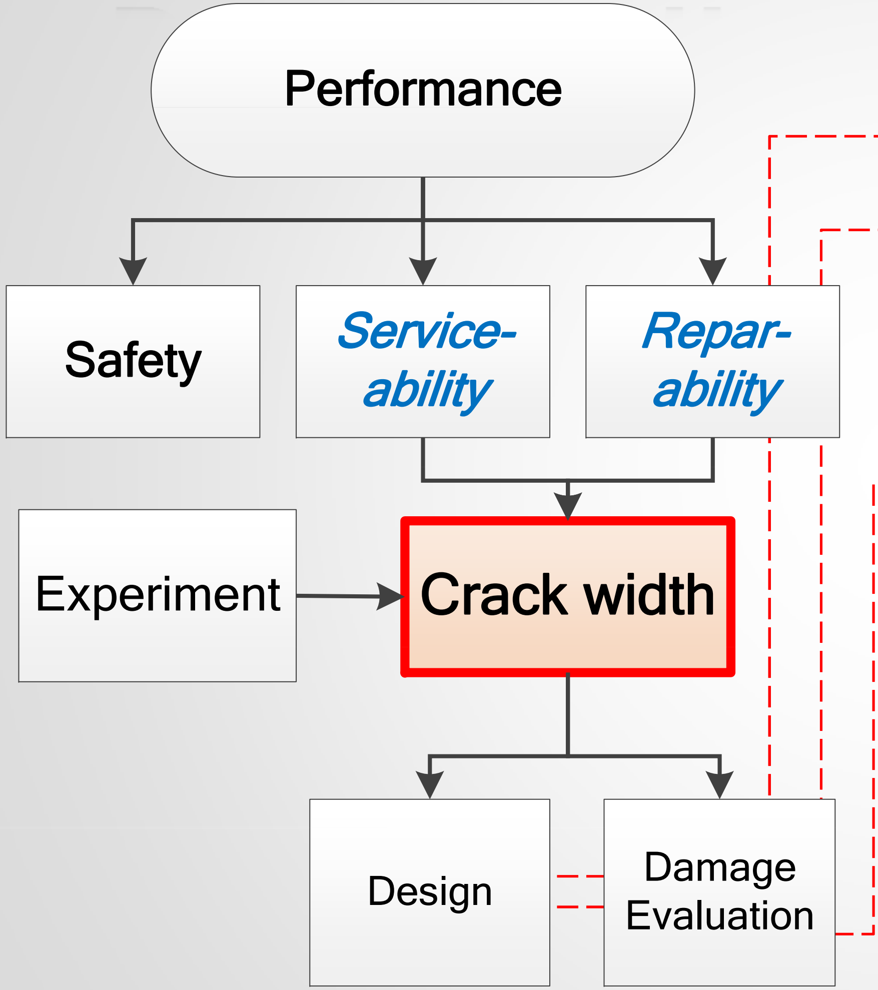
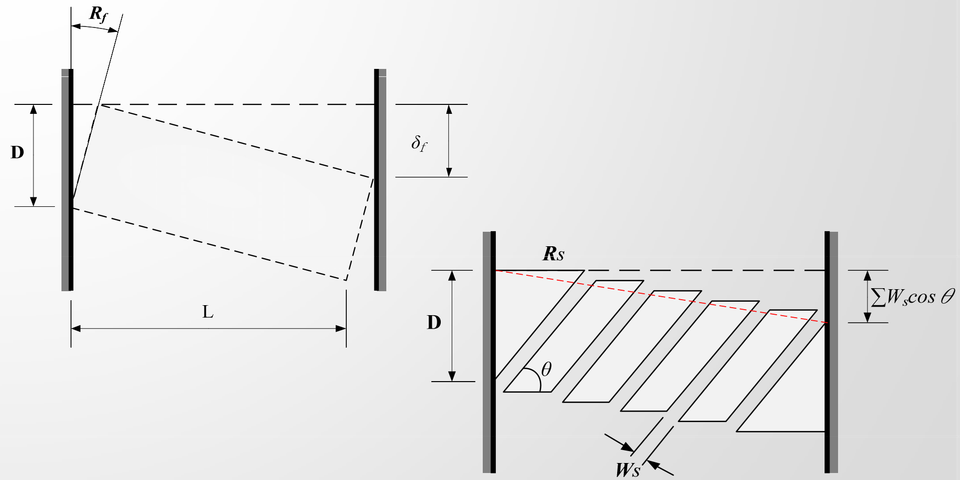
Destination



① Flexural Crack Control (ACI 318)

② Shear Crack Control (AIJ 2010)

③ Damage Evaluation
Crack Widths and Deformation



Ref：日本建築學會·鋼筋混凝土建築物之耐震性能評價指針,2004,5.梁部材の性能評価法,pp.129~168

Shear Crack Control

AIJ (2010)

Allowable shear force corresponding to serviceability ensuring

$$V_{AL1} = bj\alpha f_{cs}$$

$$V_{AL1} = bj\{\alpha f_{cs} + 0.5 f_{ss}(p_w - 0.002)\}$$

Allowable shear force corresponding reparability ensuring

$$V_{SL1} = bj\left\{\frac{2}{3}\alpha f_c + 0.5 f_s(p_w - 0.002)\right\}$$

Reinforcement

Types	Long-term allowable stress		Short-term allowable stress	
	Compression and tension	Shear	Compression and tension	Shear
SR 235	155	155	235	235
SR 295	155	195	295	295
SD 295	195	195	295	295
SD 345	215 (*195)	195	345	345
SD 390	215 (*195)	195	390	390
SD 490	215 (*195)	195	490	490

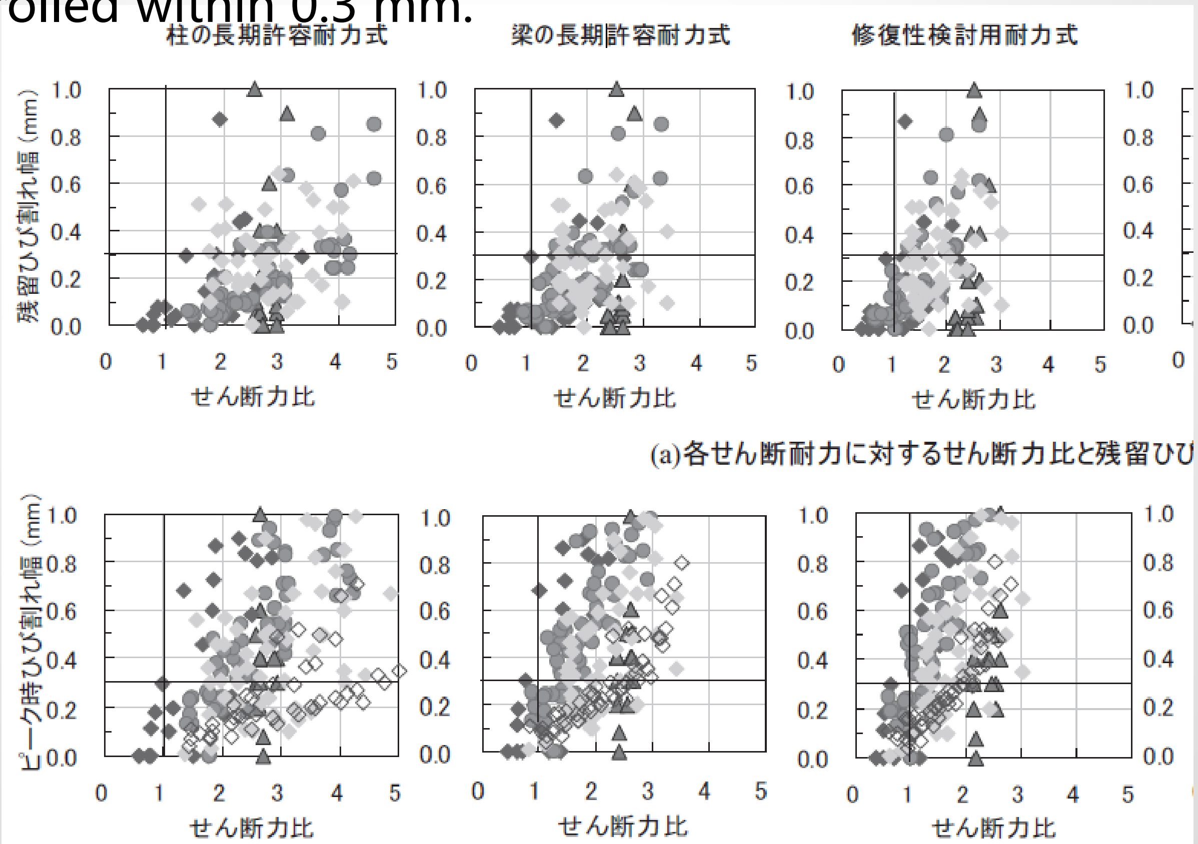
Concrete

Long-term allowable stress		Short-term allowable stress	
Compression	Shear	Compression	Shear
$\frac{1}{3} f_c'$	$\min\left\{\frac{1}{30} f_c', \left(0.49 + \frac{1}{100} f_c'\right)\right\}$	Long-term allowable stress × 2.0	Long-term allowable stress × 1.5

Shear Crack Control

AIJ (2010)

According the research conducted by Simazaki (2009), if the long-term loading is less than V_{AL1}, the *maximum shear crack width* can be controlled within 0.3 mm. If the short-term loading of a medium-magnitude is less than V_{SL1}, the *residual maximum shear crack width* can be controlled within 0.3 mm.



Flexural Crack Control

ACI-318 (2005)

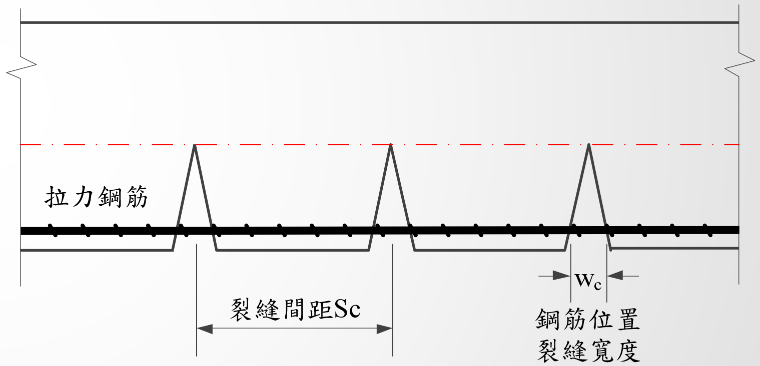
$$s \le 380\left(\frac{280}{f_s}\right) - 2.5c_c$$

$$s \le 300\left(\frac{280}{f_s}\right)$$

Ref. Robert J. Frosch (1999)

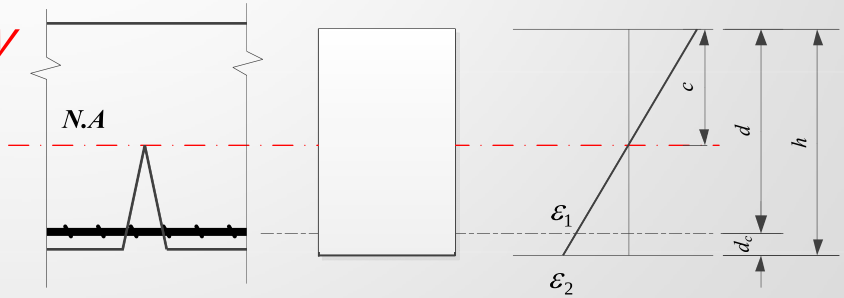
(1) Model:

$$w_c = \varepsilon_s \cdot S_c = \frac{f_s}{E_s} \cdot S_c$$



Crack width grows linearly

$$w_{max} = \frac{h-c}{d-c} \cdot w_c = \beta \cdot w_c$$



Flexural Crack Control

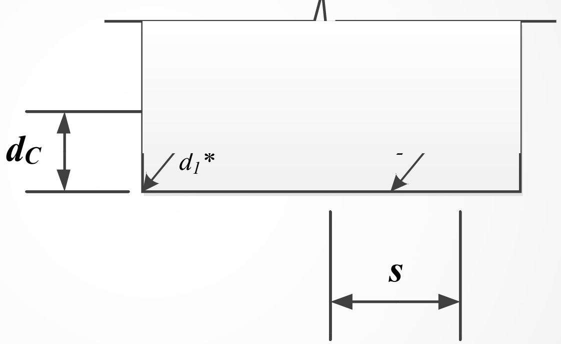
ACI-318 (2002 & 2005)

Ref. Robert J. Frosch (1999)

(2) Crack spacing

From the bar center to the farthest concrete element

$$w_{max} = \frac{h-c}{d-c} \cdot \frac{f_s}{E_s} \cdot S_c$$



$$d_1^* = \sqrt{d_c^2 + d_c^2}$$

$$d_2^* = \sqrt{d_c^2 + (\frac{s}{2})^2}$$

Control !

Minimum crack spacing = $1.0 \times d_2^*$

Average crack spacing = $1.5 \times d_2^*$

Maximum crack spacing = $2.0 \times d_2^*$

$$w_{max} = \beta \cdot \frac{f_s}{E_s} \cdot 2\sqrt{d_c^2 + (\frac{s}{2})^2}$$

Ref：Robert J. Frosch, 1999, Another Look at Cracking Control in Reinforced Concrete, ACI Structural Journal

Flexural Crack Control

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ACI-318 (2002 & 2005)

$$s = 380\frac{250}{f_s} - 2.5C_c \le \frac{300 \cdot 252}{f_s}$$ 0.41 mm

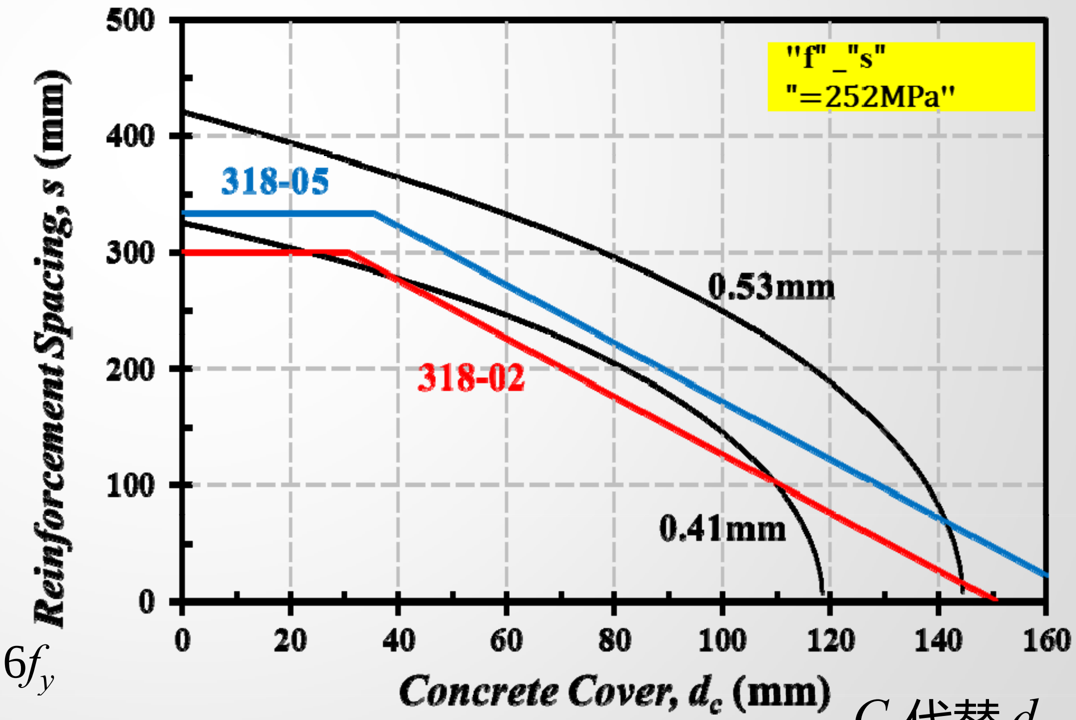
$$s = 380\frac{280}{f_s} - 2.5C_c \le \frac{300 \cdot 280}{f_s}$$ 0.41-0.53 mm

Ref. Robert J. Frosch (1999)

(3) Crack control

$$w_{max} = \beta \cdot \frac{f_s}{E_s} \cdot 2\sqrt{d_c^2 + (\frac{s}{2})^2}$$

$$s = 2\sqrt{(\frac{w_{max}E_s}{2\beta f_s})^2 - d_c^2}$$



C_c代替 d_c

Crack width：0.41 mm

Tensile stress of main bars：$0.6f_y$

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Ref：Robert J. Frosch, 1999, Another Look at Cracking Control in Reinforced Concrete, ACI Structural Journal

Experiment

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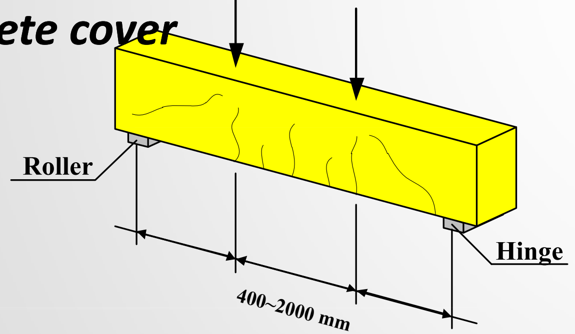
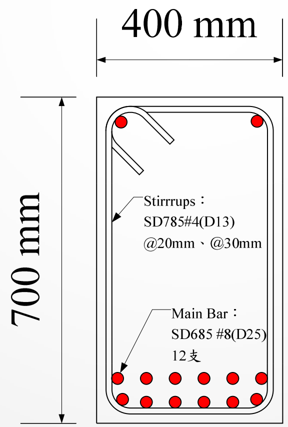
Specimen Design

Yielding stress	685、785MPa
Reinforcement size	D32(#10)、D25(#8)
Compressive strength	70、100MPa
Section size	70×40、50×35 (cm²)

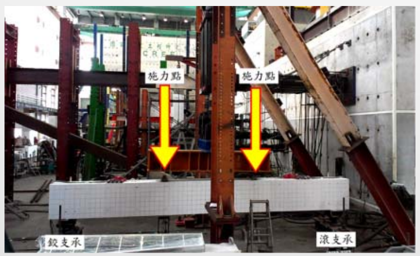
Chiu et al. (2015)

Concrete cover



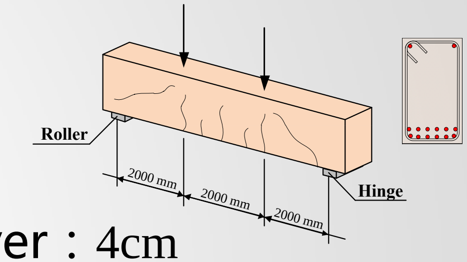


Number：2
Concrete cover：2、3cm



Chiu et al. (2013)

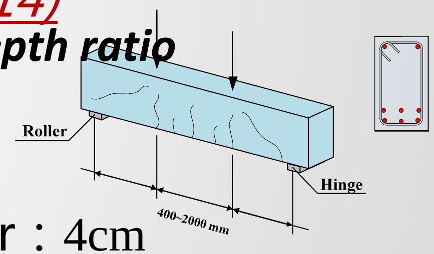
Stirrup ratio



Number：10
Concrete cover：4cm

Chiu et al. (2014)

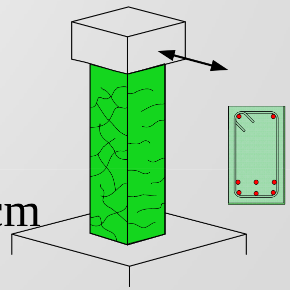
Shear span to depth ratio



Number：10
Concrete cover：4cm

Cheng et al. (2014)

Cyclic loading



Number：3
Concrete cover：3cm

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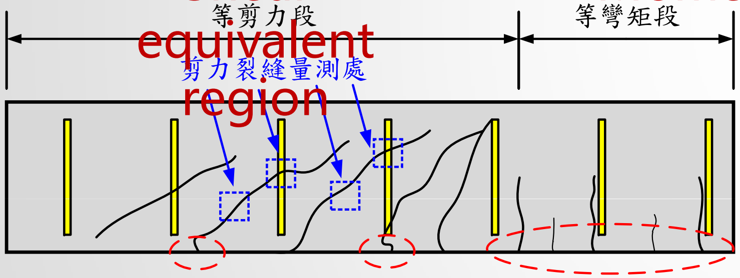
Experiment

Measurement system

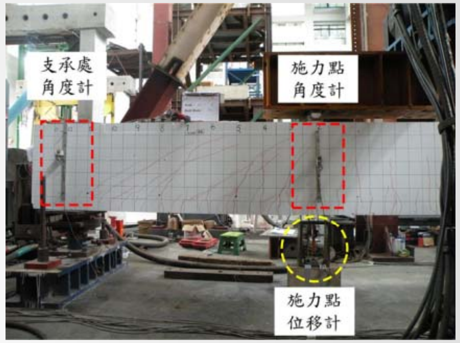
1. Crack measurement

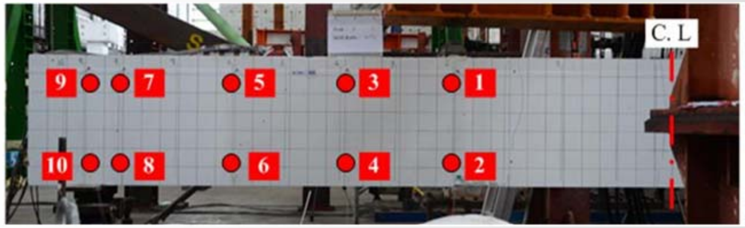
Shear-equivalent region

Moment-equivalent region

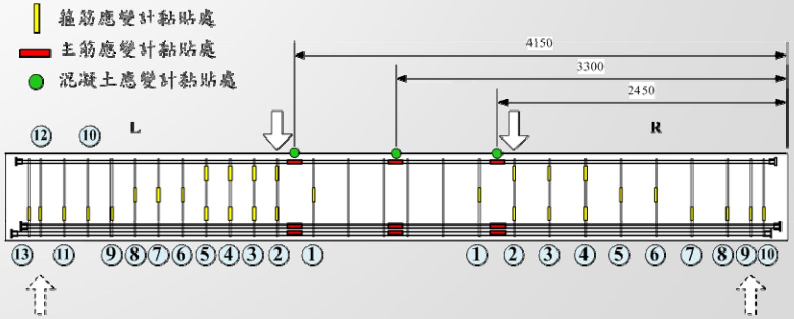


2. NDI





3. Strain of reinforcement



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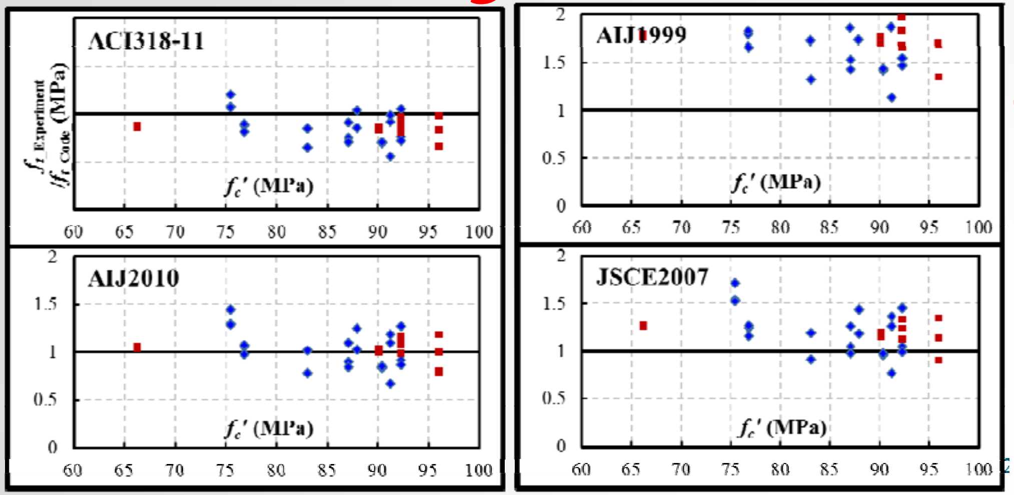
Shear Crack

Tensile Strength of Concrete

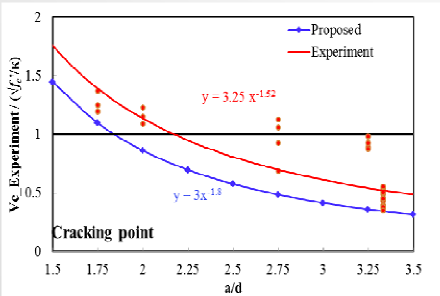


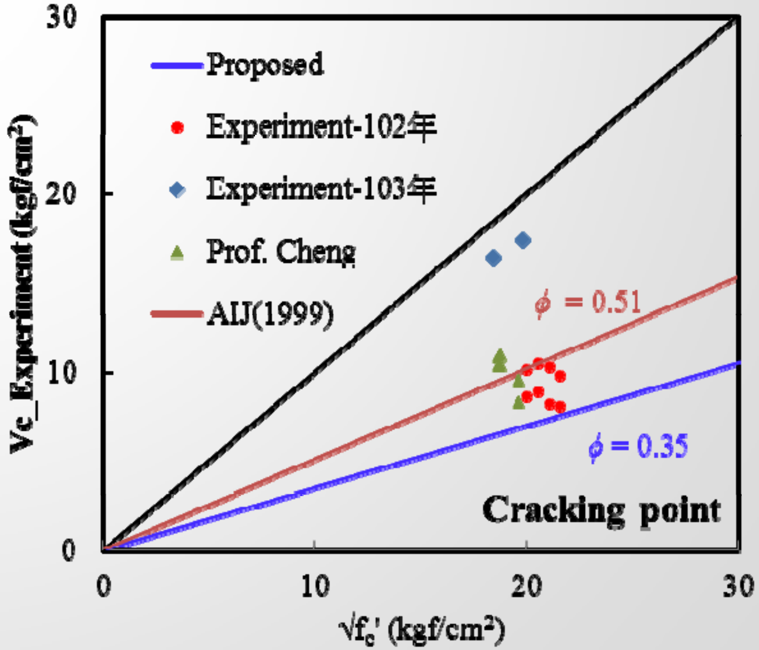
AIJ1999	$0.33\sqrt{f_c'}$	MPa
AIJ2010	$0.56\sqrt{f_c'}$	MPa
JSCE2007	$0.23{f'_c}^{2/3}$	MPa

Shear Crack Strength of Concrete

$$v_{cr} = \eta_{cr} \times 0.33\sqrt{f_c'}/\kappa \text{ (MPa)}$$

$$\eta_{cr} = 3\left(\frac{a}{d}\right)^{-1.8} \quad (0.35 \le \eta_{cr} \le 1.0)$$





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Experimental Data

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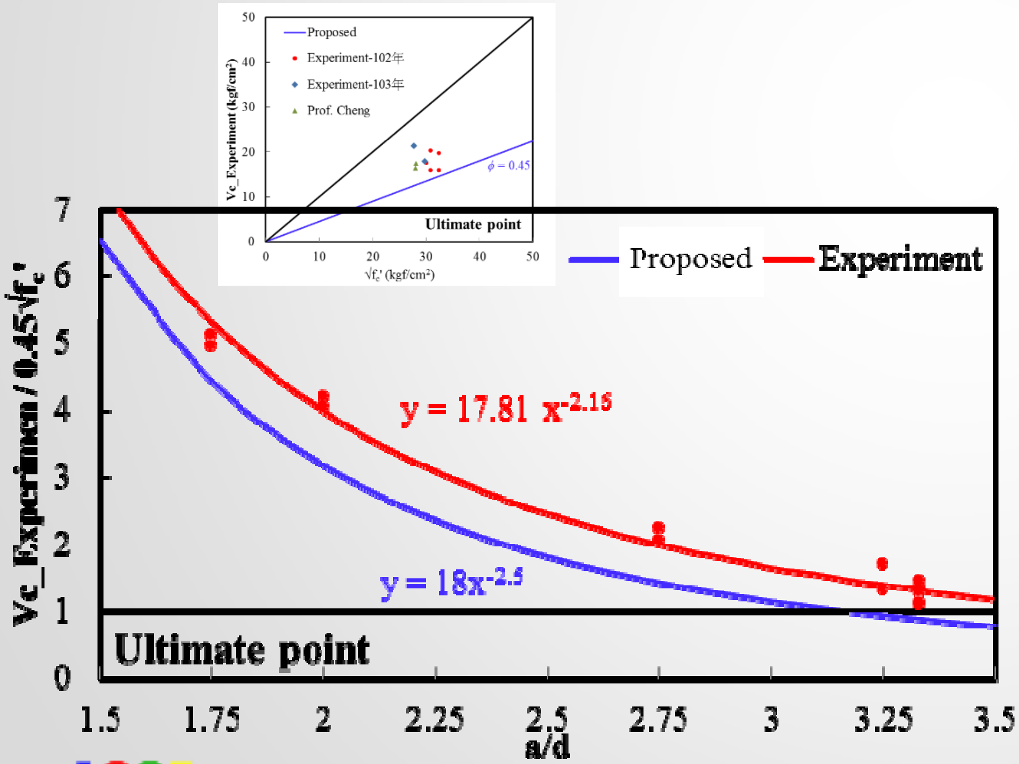
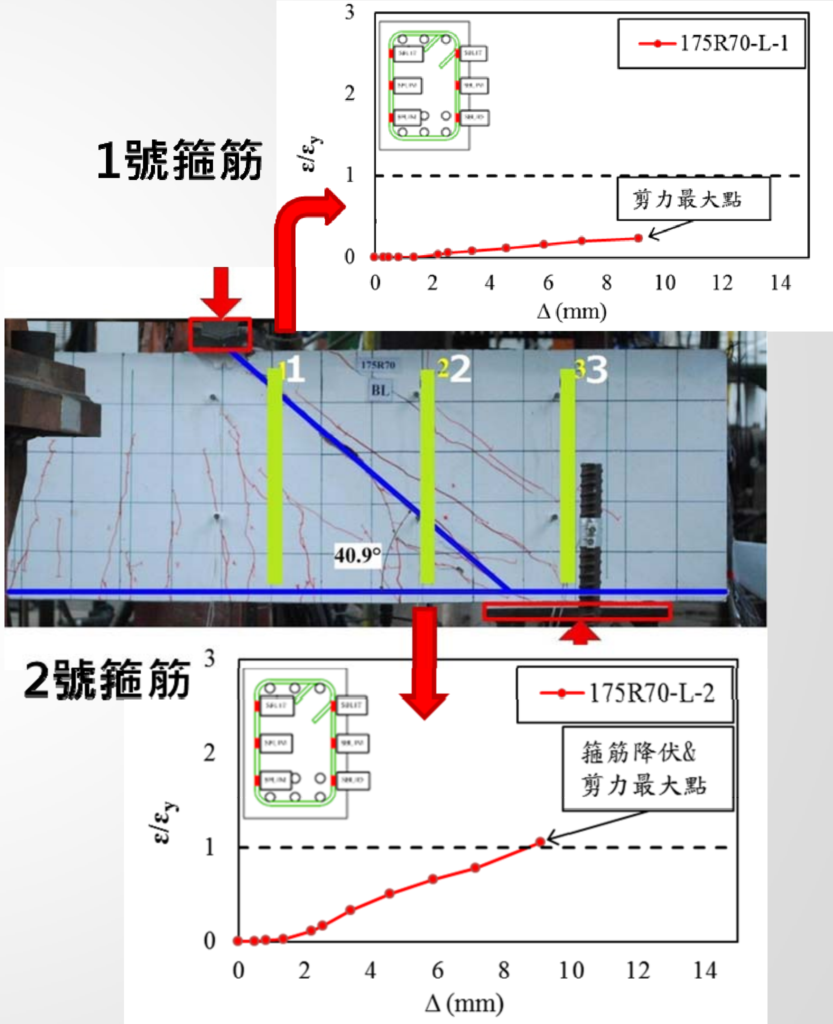
Shear Crack

Ultimate Shear Strength of Concrete

$$v_{cu} = 0.45\eta_{cu} \times 0.33\sqrt{f_c'}\ (\text{MPa})$$

$$\eta_{cu} = 18\left(\frac{a}{d}\right)^{-2.5};\ (1 \le \eta_{cu} \le 4)\ (\text{MPa})$$





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Experimental Data

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Shear Crack

$$v_{c\_ser} = v_{cr}$$

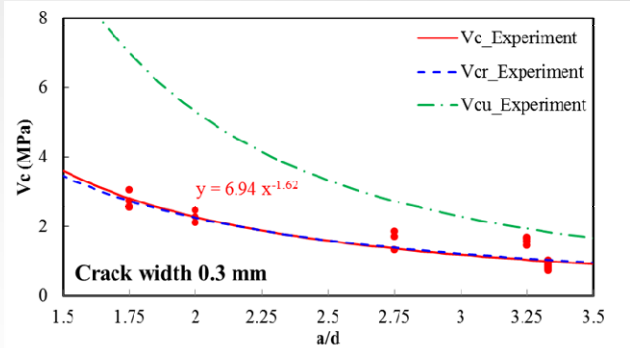
$$v_{cr} = \eta_{cr} \times 0.33\sqrt{f_c'}/\kappa \text{ (MPa)}$$

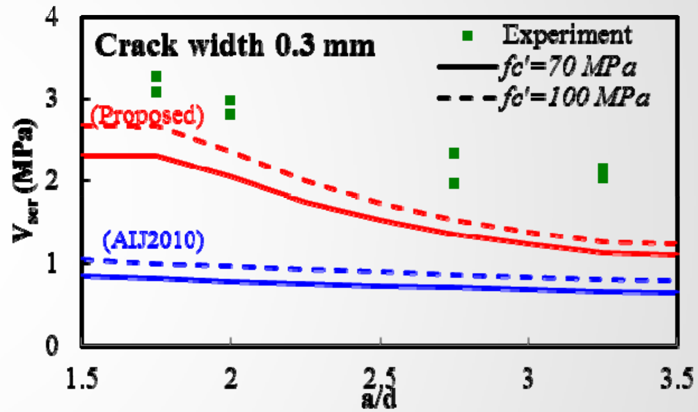
$$\eta_{cr} = 3\left(\frac{a}{d}\right)^{-1.8} \quad (0.35 \le \eta_{cr} \le 1.0)$$

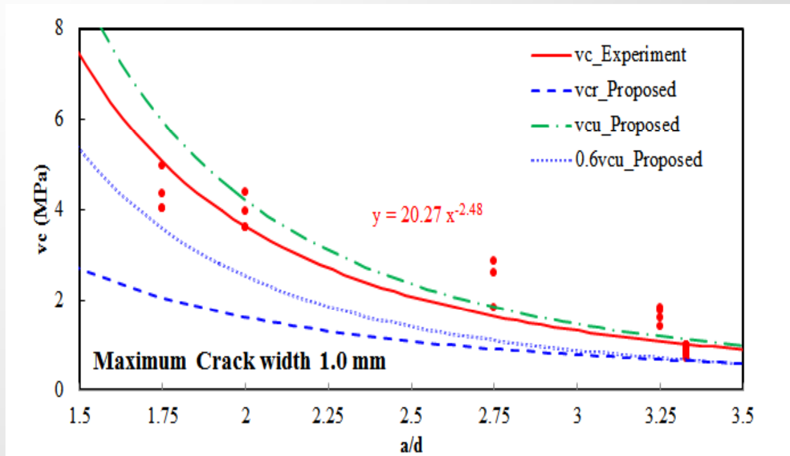
$$v_{c\_rep} = 0.6v_{cu}$$

$$v_{cu} = 0.45\eta_{cu} \times 0.33\sqrt{f_c'} \text{ (MPa)}$$

$$\eta_{cu} = 18\left(\frac{a}{d}\right)^{-2.5} ; (1 \le \eta_{cu} \le 4) \text{ (MPa)}$$







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Shear Crack Control

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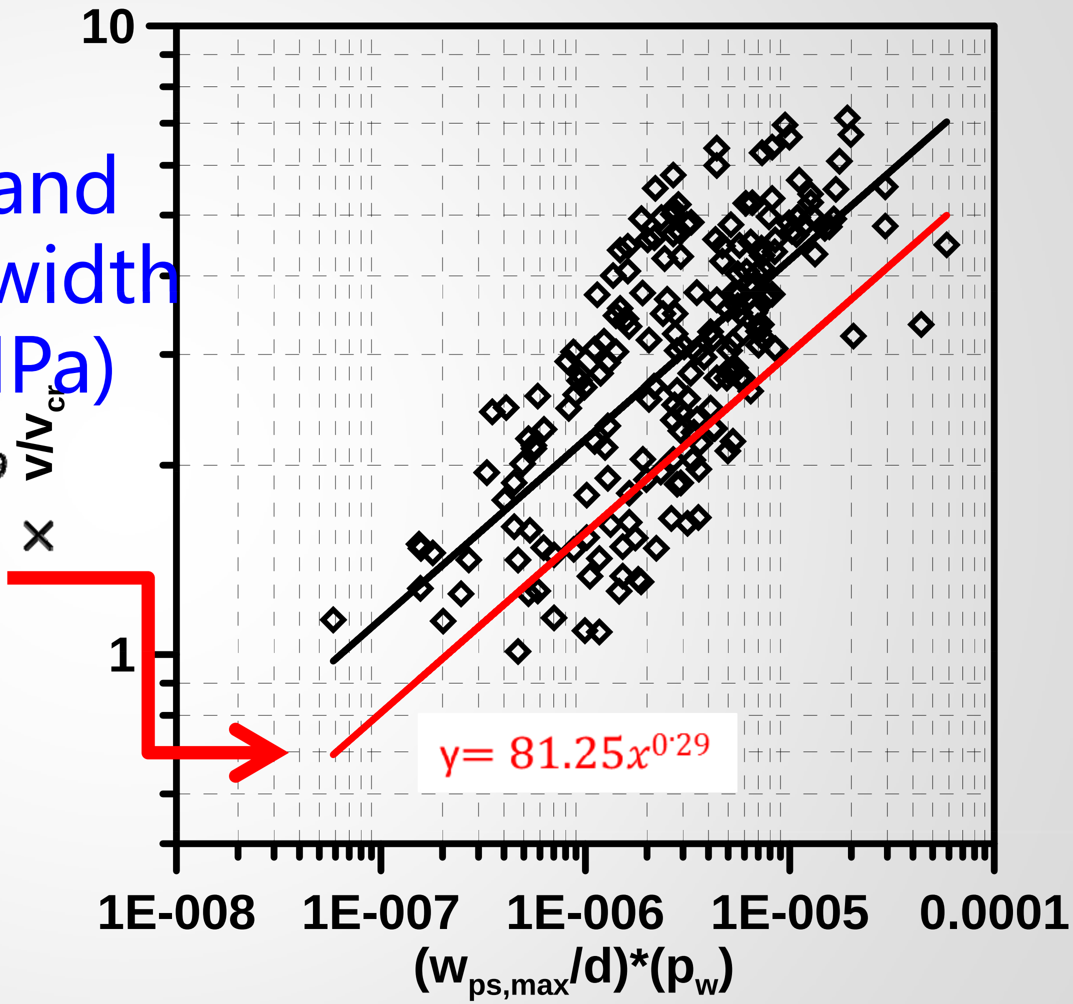
Design Formula

Average shear stress and
Maximum Shear crack width
(Reinforcement 785MPa)

$$V = 81.25 \times \left\{\left(\frac{W_{ps,max}}{d}\right) \times \rho_{ts}\right\}^{0.29} \times \left(\eta_{cr} \times \left(0.33\sqrt{f'_c}\right) \times bD/1.5\right)$$

$$\rho_{ts} = \frac{A_v}{bd}$$



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Experimental Data

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Shear Crack

Allowable Shear Stress
(Maximum shear crack width0.3 mm)

$$V_c = \frac{(V_{u,1mm} - V_{sc})}{(1.0 - 0.3)} \times (W_{p,max} - 0.3) + V_{sc}$$

$$V_s = V - V_c = \rho_{ts} f_s bd$$

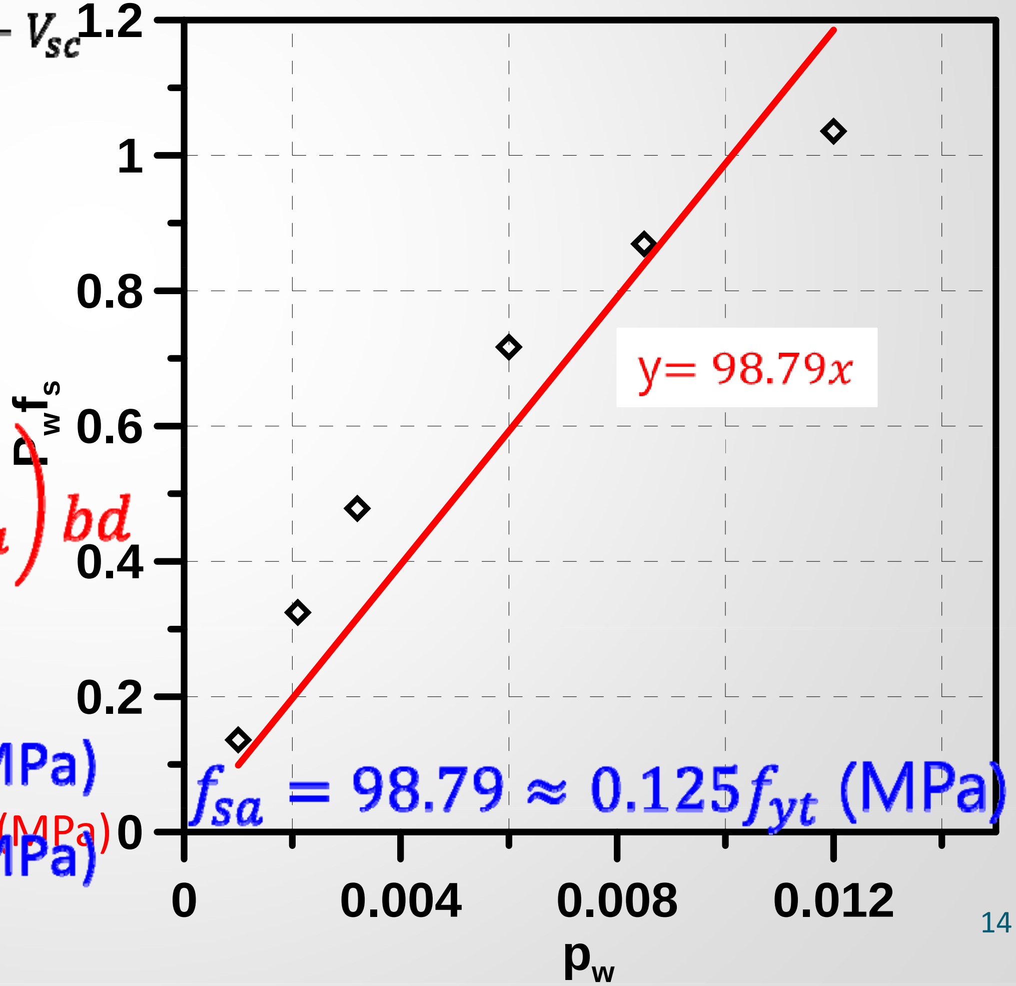
$$f_{st} = \frac{V - V_c}{\rho_{ts} bd}$$

$$V_{sa} = \left(\frac{\eta_{cr} \times 0.33\sqrt{f_c'}}{1.5} + \rho_{ts} f_{sa}\right) bd$$

$$\eta_{cr} = 3 \times \left({}^{a}/_{d}\right)^{-1.8} ; 0.35 \le \emptyset \le 1.0$$

$f_{sa}\ (0.3\ mm) = 0.125 f_{yt}$ (MPa)

$f_{sa}\ (0.4\ mm) = 0.150 f_{yt}$ (MPa)



$f_{sa} = 98.79 \approx 0.125 f_{yt}$ (MPa)

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Experimental Data

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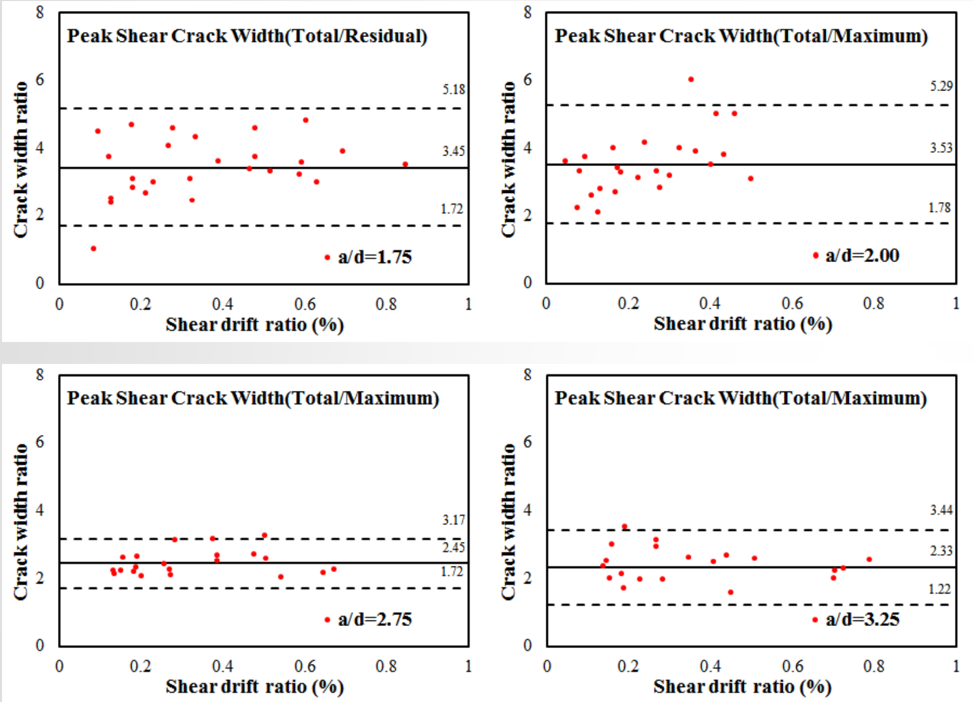
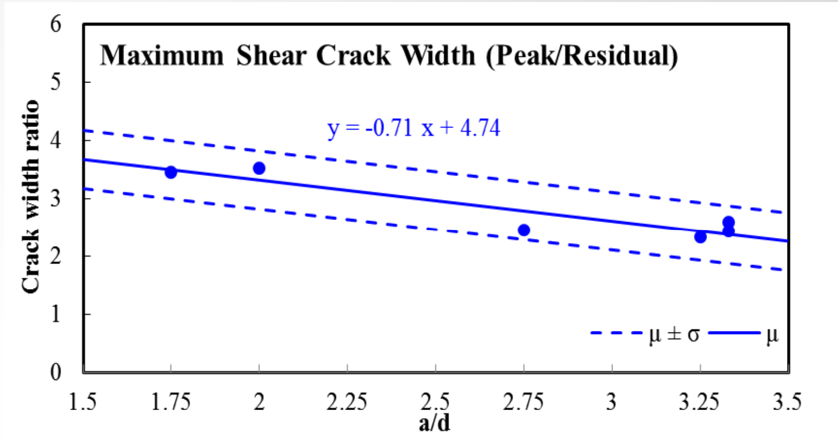
Shear Crack





$$n_{s\_Maximum} = -0.71 \times \left(\frac{a}{d}\right) + 4.74$$

Allowable Shear Stress
(Maximum shear crack width 1.0 mm)

$$f_{sa}\ (1.0\ mm) = 0.20 f_{yt}\ \text{(MPa)}$$

Allowable Shear Stress (Maximum residual shear crack width 0.4 mm)

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Shear Crack Control

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Design Formula

Performance			Allowable shear stress (MPa)
Long-term	Serviceability	Shear crack strength	$v_{cr} = \eta_{cr} \times 0.33\sqrt{f_c'}/1.5$ $\eta_{cr} = 3\left(\frac{a}{d}\right)^{-1.8} \quad (0.35 \le \eta_{cr} \le 1.0)$
		Maximum shear crack width 0.4mm	$v_{ser} = \eta_{cr} \times 0.33\sqrt{f_c'}/1.5 + 0.15\rho_{ts} f_{yt}$
Short-term	Reparability	Maximum shear crack width 1.0 mm	$v_{rep} = 0.27\eta_{cu} \times 0.33\sqrt{f_c'} + 0.20\rho_{ts} f_{yt}$ $\eta_{cu} = 18\left(\frac{a}{d}\right)^{-2.5};\ (1 \le \eta_{cu} \le 4)$

Shear Crack Control

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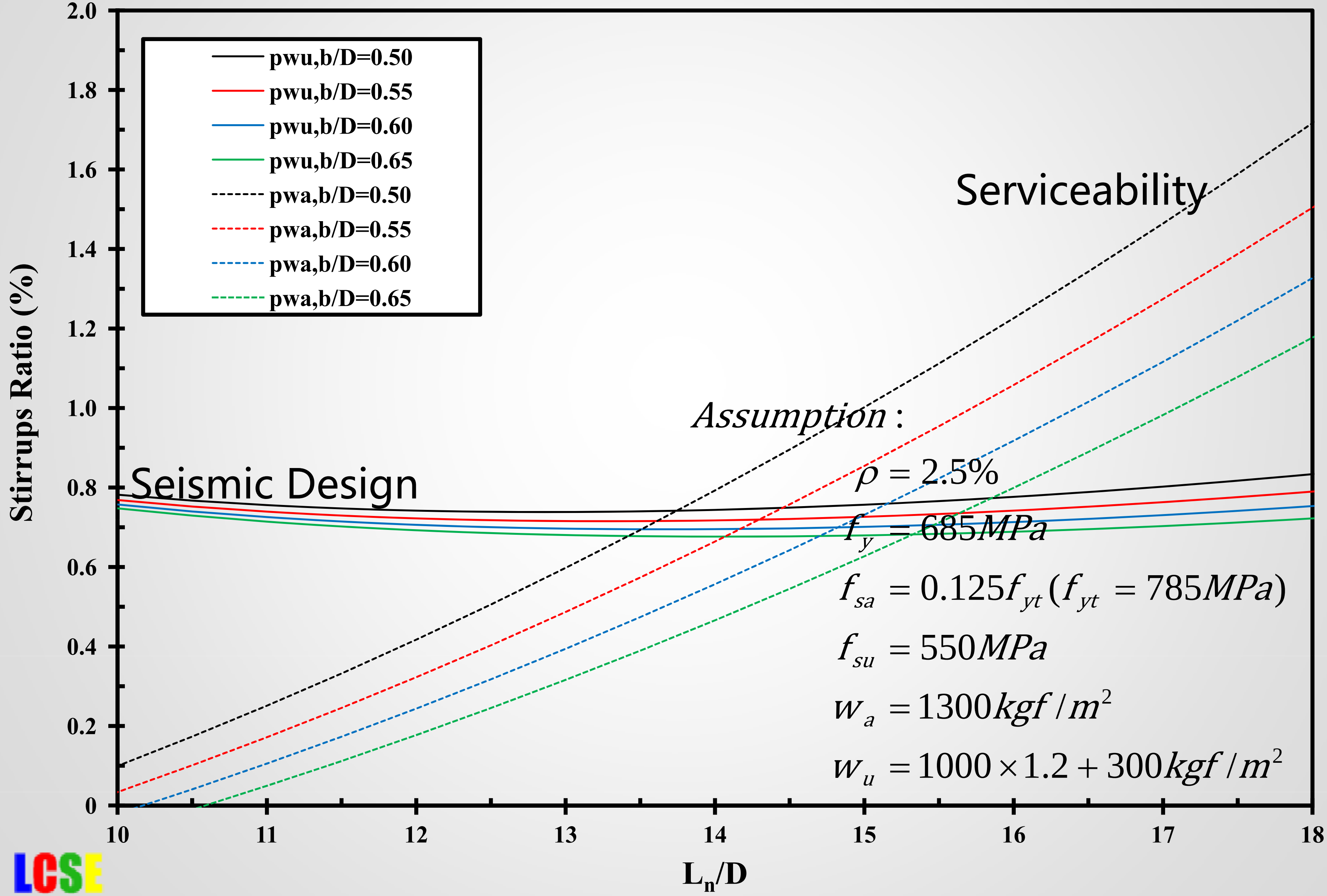
Design Formula



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Shear Crack Control

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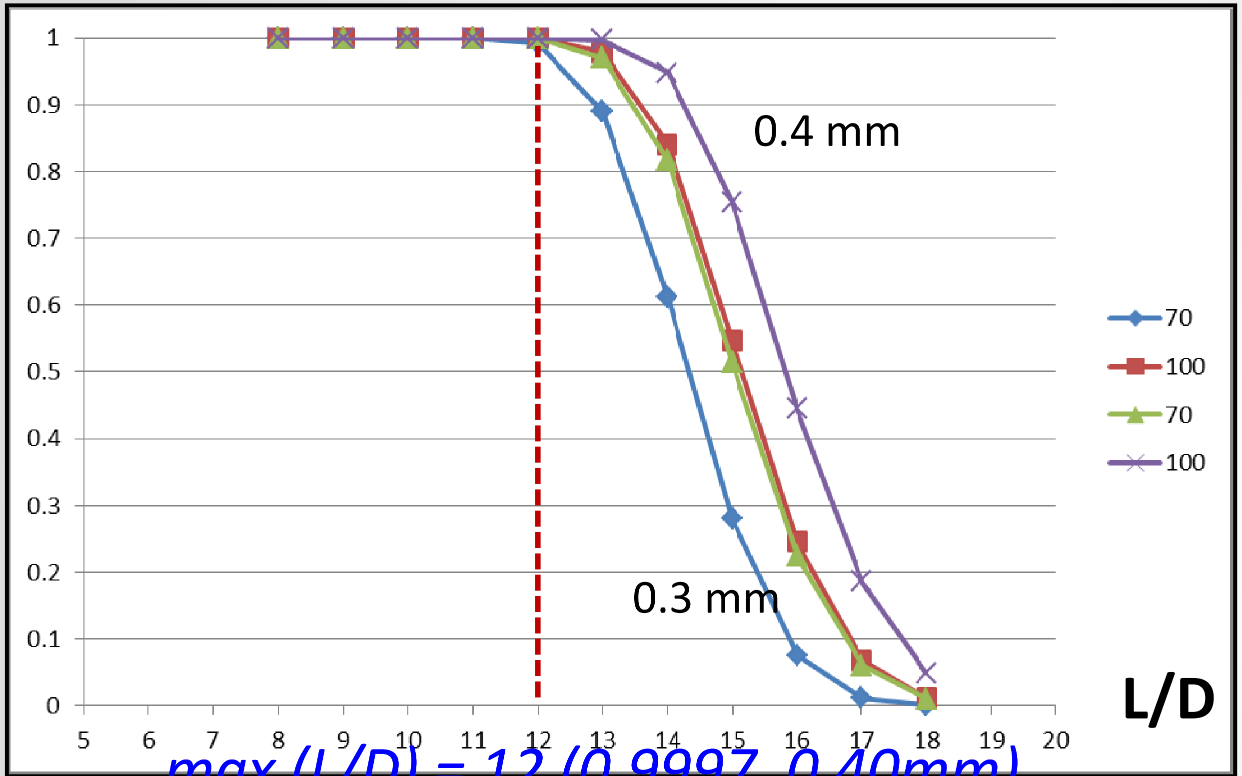
Design Formula



max (L/D) = 12 (0.9997, 0.40mm)

$$\rho_{ts,u} = \left(C_1 / \left(\frac{L}{D} \right) + C_2 (\frac{L}{D})^2 \right) / f_{su}$$

$$\rho_{ts,a} = \left(C_3 \left(\frac{L}{D} \right)^2 - v_{cr} \right) / f_{sa}$$

$$G(L/D) = \frac{\rho_{ts,u}}{\rho_{ts,a}} - 1$$

Reliability

Random variables

b/D: 0.45-0.55
B/L: 0.5-1.0
Dead Load : 800-1100 kgf/m
Live Load: 200-400 kgf/m^2

MCS

f_y: 685 Mpa
f_{yt}: 785 Mpa
f_{su}: 550 MPa
f_{sa}: 0.125or 0.15 f_{yt}

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Flexural Crack Control

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手冊建議, 4.3.2

$$v_{ser} = \frac{0.35\sqrt{f_c'}}{1.5} + \frac{A_v f_s}{b_w s} \qquad v_{ser} = \frac{0.35 \times 0.33\sqrt{f_c'}}{1.5} + \frac{A_v f_s}{b_w s}$$

f_s為剪力鋼筋之容許應力，最大值為0.15f_{yt}

[解說]設計剪應力之計算可參考ACI318之建議，$v=V/(b_w d)$。計算梁構件於靜載重與活載重下之斷面剪應力時，不須考慮兩載重之載重放大因子。式(4.3.1)之前項為混凝土之容許應力，依實驗結果可知，其與構件之剪力跨距與深度比有密切相關，就一般中長梁而言則建議採用0.35[3]。由式(4.3.1)可知，梁構件可藉由剪力鋼筋之用量以提升其容許應力。若梁構件之跨深比增加，為有效控制靜載重與活載重下之剪力裂縫，則具所需之剪力鋼筋用量亦會增加，並會大於耐震設計下剪力鋼筋量；反之，若能將梁構件之跨深比降至12以下，則耐震設計下剪力鋼筋需求會主控設計，而不須檢核本節規定[3]。

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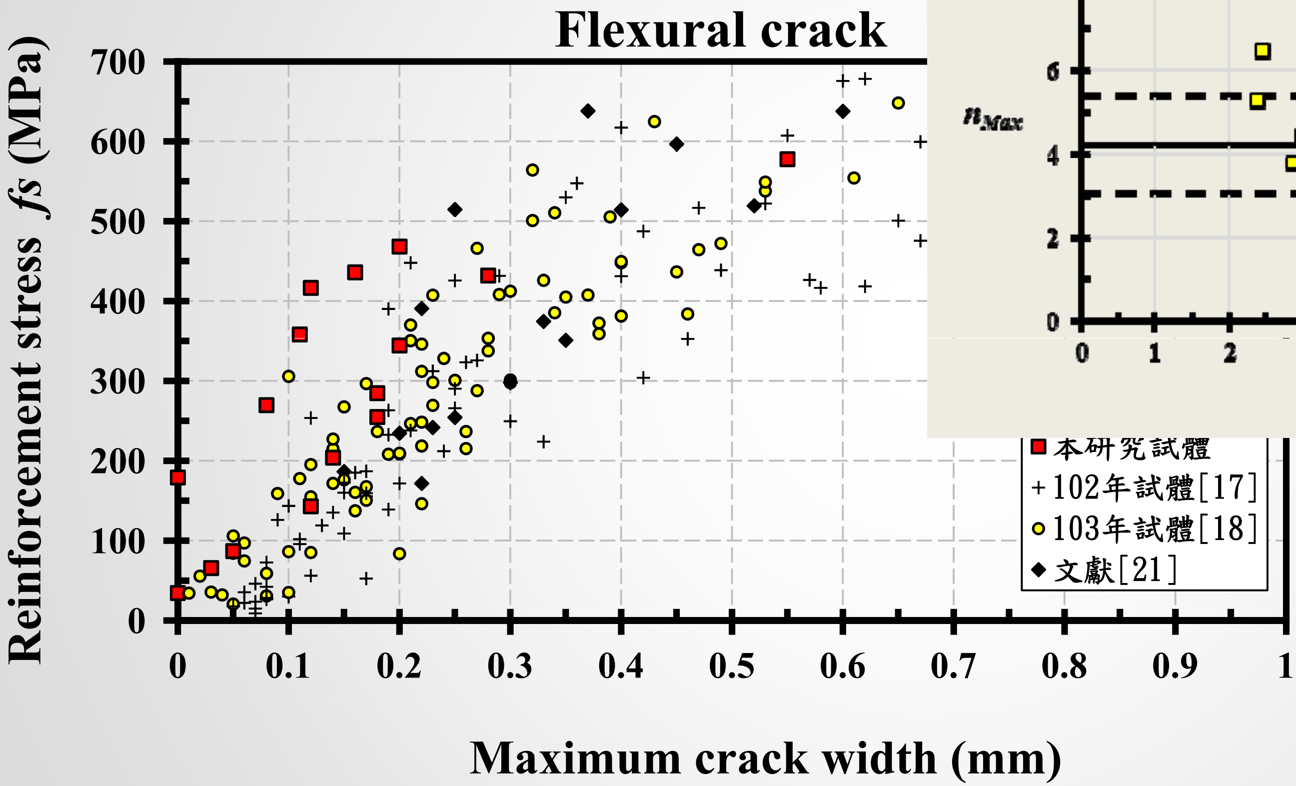
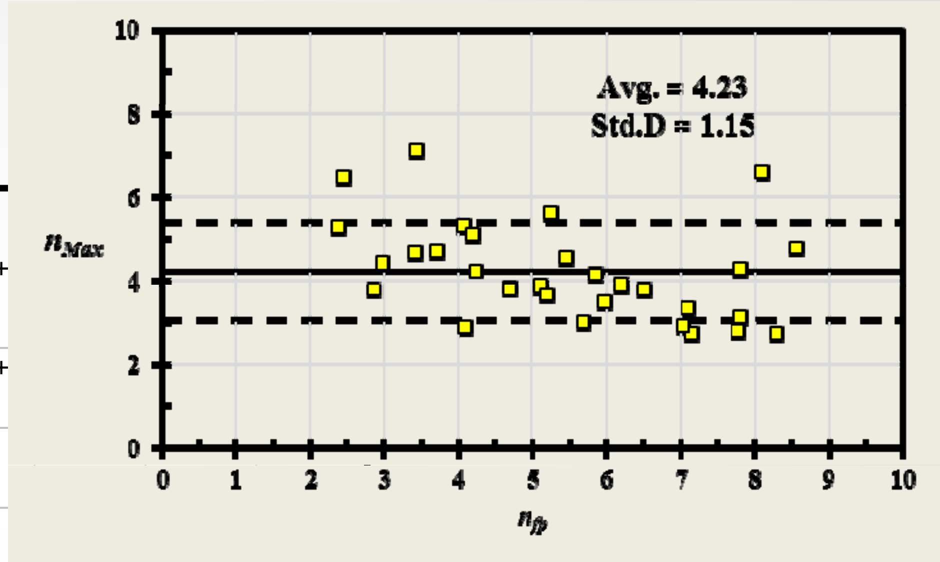
Experimental Data

Flexural Crack





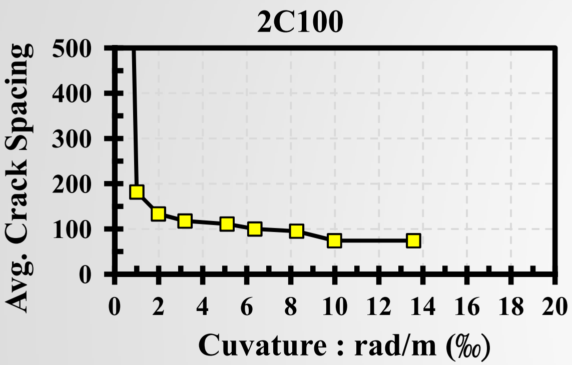
$$n_{f\_Maximum} = 4.23$$

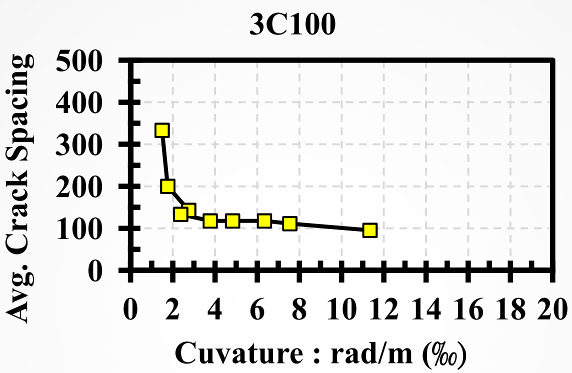
Crack width is proportional to reinforcement stress

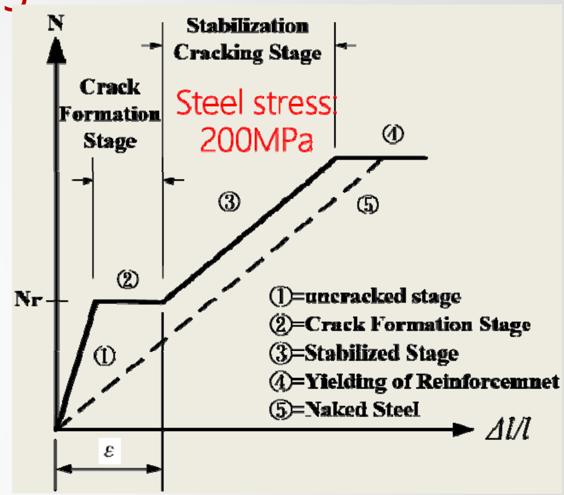
Experimental Data

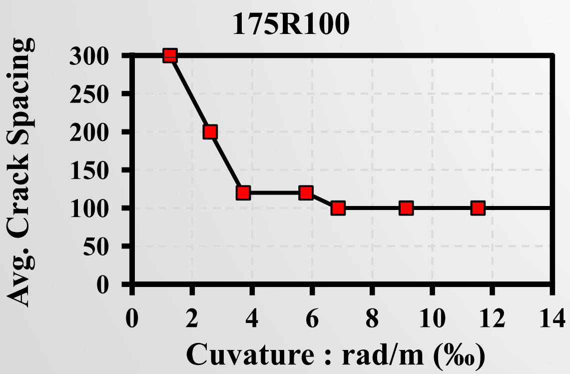
Flexural Crack

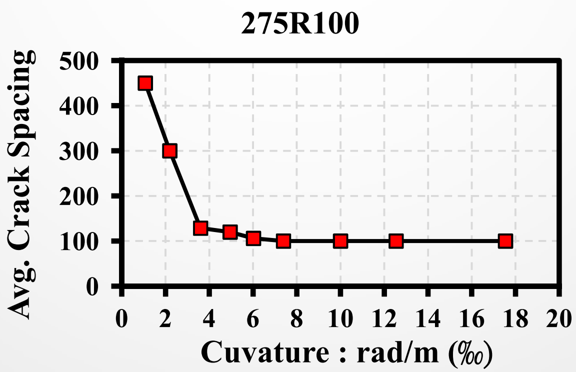
Stable →Crack number not increased →Crack spacing turns to be constant

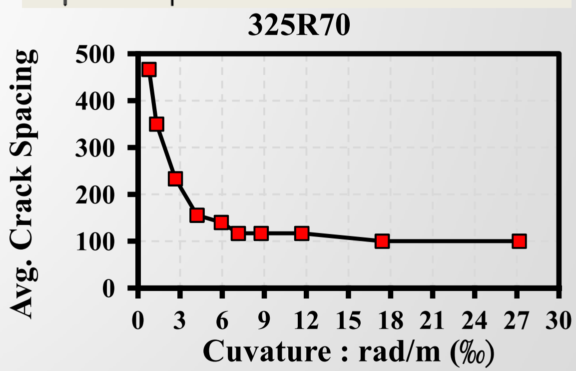












Average crack spacing = Crack numbers / Span of the moment-equivalent region

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Average Crack Spacing

Crack width = (strain)(crack spacing)

ACI 318 (2002 & 2005)	$w_{max} = \frac{f_s}{E_s}\beta\ 2\sqrt{d_c^2 + (\frac{s}{2})^2}$
AIJ-2010 (附錄)	$w_{max} = 1.5(\varepsilon_{s,av} + \varepsilon_{sh})\ \{2\left(c + \frac{s}{10}\right) + k\frac{\phi}{p_e}\}$
JSCE-2007	$w_{max} = [\frac{\sigma_{se}}{E_s} + \varepsilon'_{csd}]\ 1.1k_1k_2k_3\{4c + 0.7(c_s - \phi)\}$
CEB-FIP	$w_{max} = (\varepsilon_{sm} - \varepsilon_{cm})(k_3c + \frac{k_1k_2k_4\phi}{\rho_{p,eff}})$
Broms	$w_{max} = 1.66\frac{f_s}{E_s}\ \ 2d_c$
趙唯堅與丸山	$w_{max} = 1.5\{\frac{\sigma_s}{E_s} - \frac{\sigma_{ctm}}{E_s p_e} - \varepsilon_\phi\}\ \frac{1}{\alpha}k_1k_2(4c + 0.7e)$

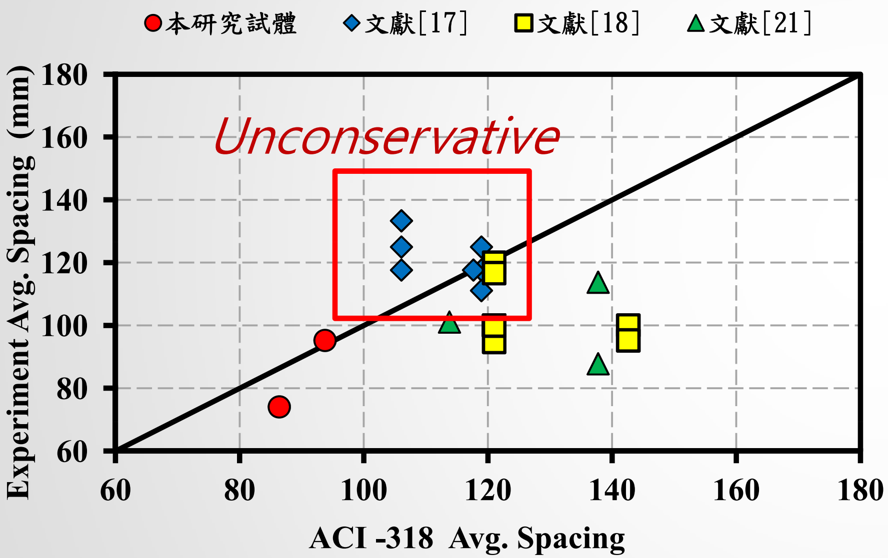
LCSE

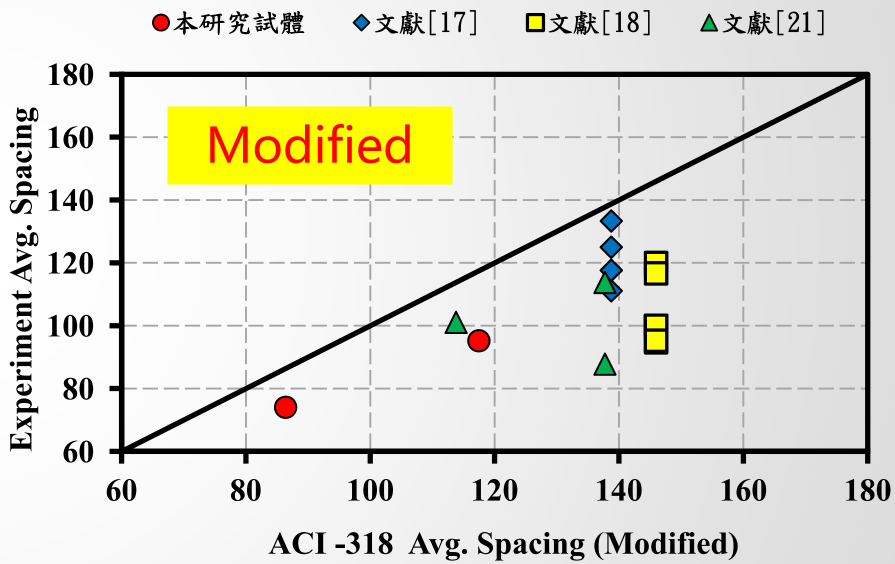
Experimental Data

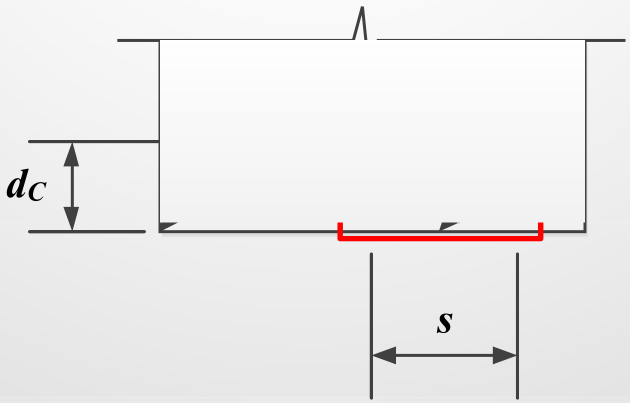
TAIWAN TECH

Flexural Crack-Average Crack Spacing

$$\text{ACI-318}: \sqrt{d_c^2 + (\frac{s}{2})^2} \Rightarrow Max[d_1^*, d_2^*]$$







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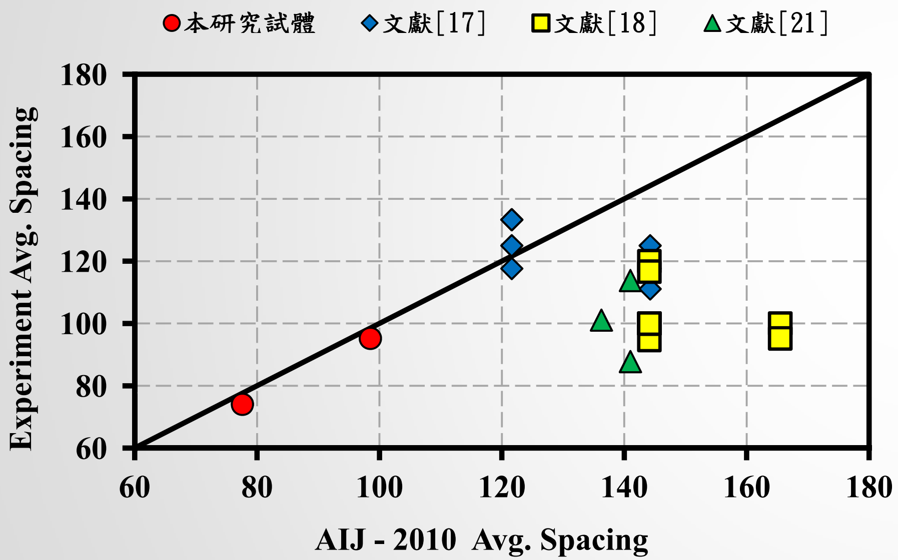
Experimental Data

TAIWAN TECH

Flexural Crack-Average Crack Spacing

AIJ-2010 (附錄)

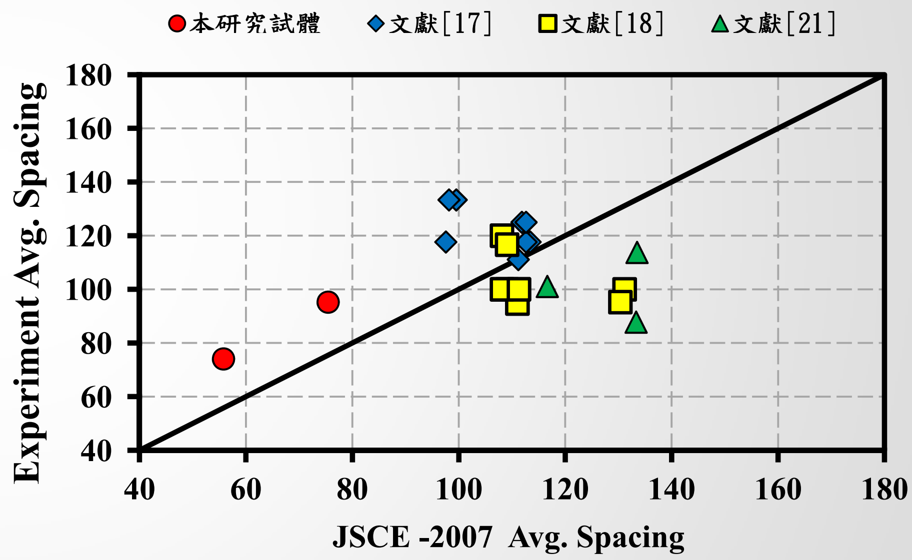


$$V_c = \frac{(V_{u,1mm} - V_{sc})}{(1.0 - 0.3)} \times (W_{p,max} - 0.3) + V_{sc}$$

$$V_s = V - V_c = \rho_{ts} f_s bd$$

$$f_{st} = \frac{V - V_c}{\rho_{ts} bd}$$

JSCE-2007



$$1.1 k_1 k_2 k_3 \{4c + 0.7(c_s - \phi)\}$$

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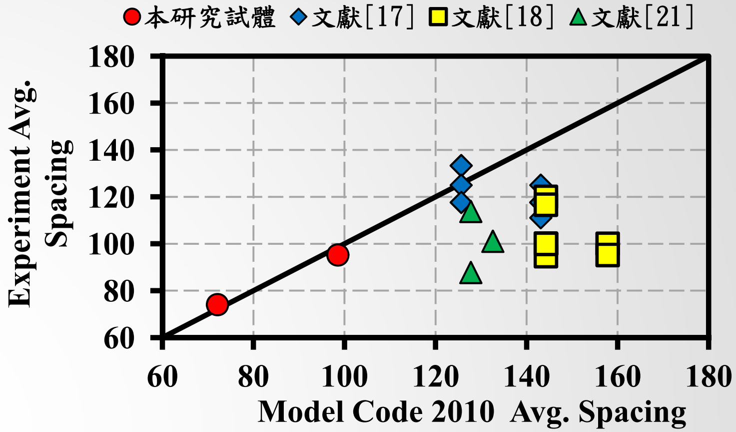
Experimental Data

TAIWAN TECH

Flexural Crack-Average Crack Spacing

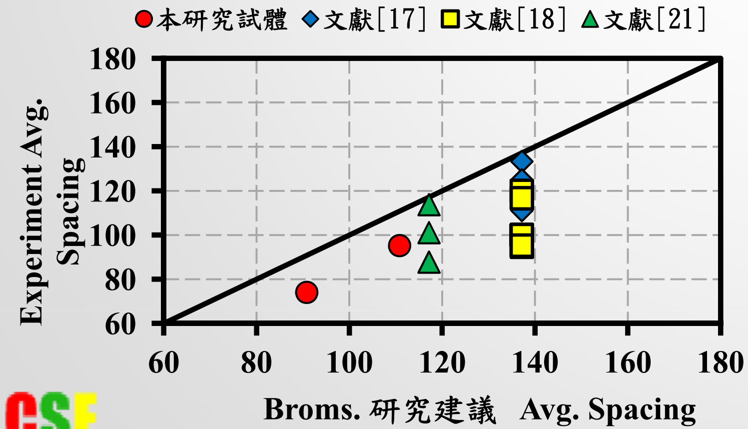
CEB-FIP

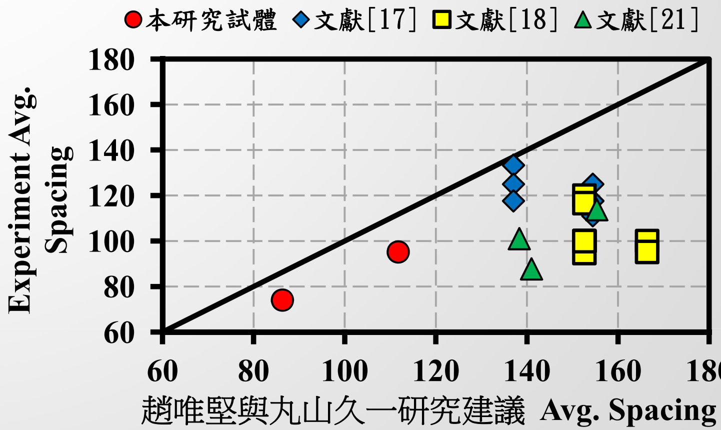
$$\left(k_3c + \frac{k_1k_2k_4\phi}{\rho_{p,eff}}\right)$$



Broms $2d_c$

趙唯堅與丸山 $\frac{1}{\alpha}k_1k_2(4c+0.7e)$





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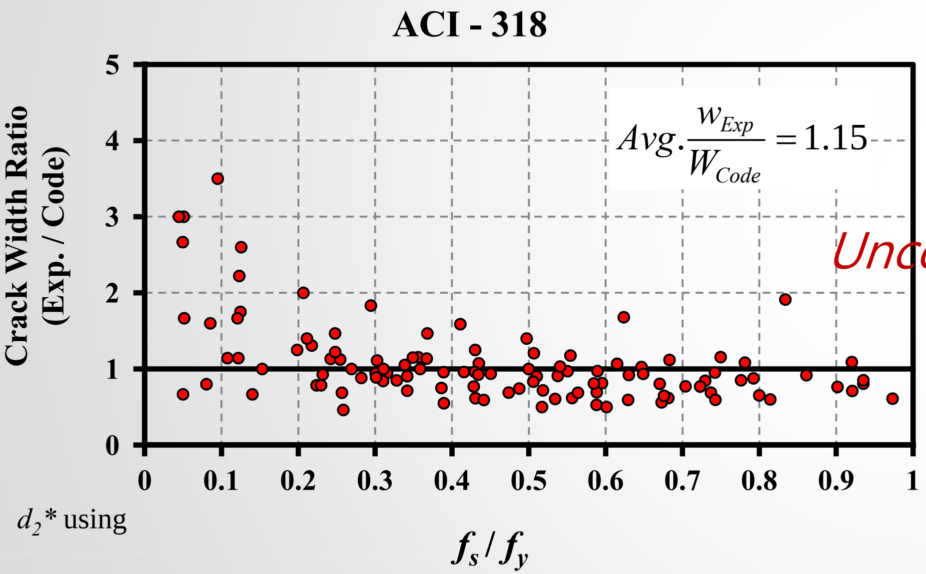
Experimental Data

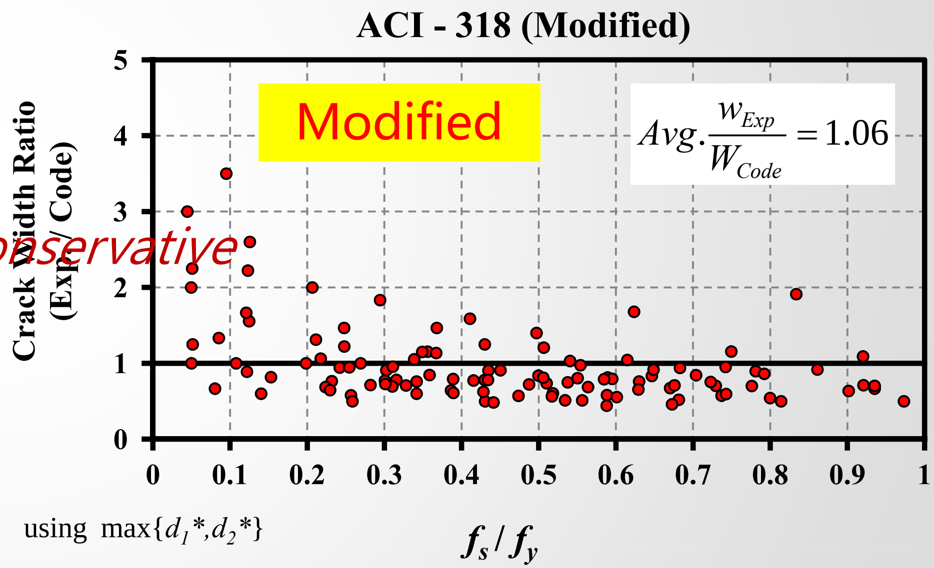
TAIWAN TECH

Flexural Crack Width

ACI 318 (2002 & 2005)



d_2* using



Unconservative

using max{d_1*,d_2*}

$$w_{max} = \frac{f_s}{E_s}\beta\ 2\sqrt{d_c^2 + \left(\frac{s}{2}\right)^2}$$

$$w_{max} = \frac{f_s}{E_s}\beta\ 2 \times \max[d_1^*, d_2^*]$$

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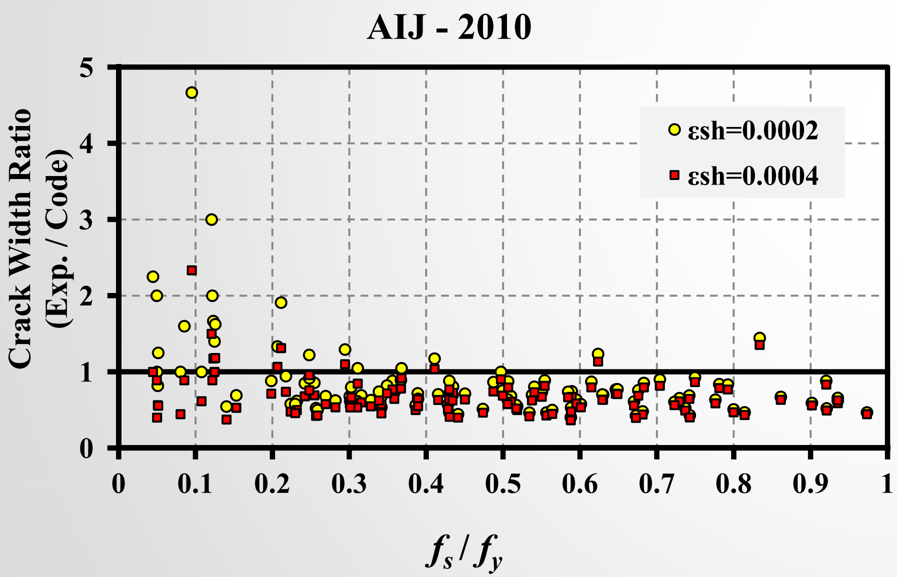
Experimental Data

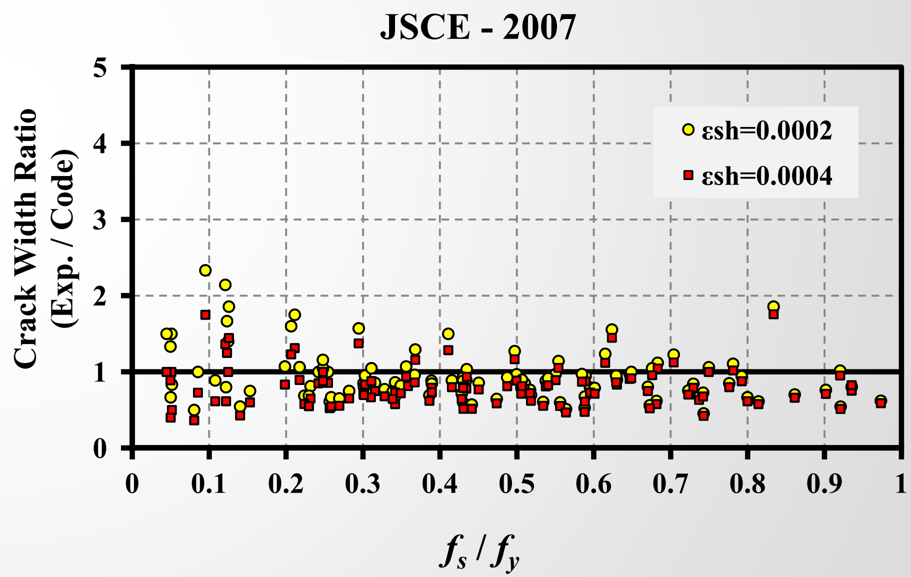
TAIWAN TECH

Flexural Crack-Average Crack Spacing

AIJ-2010(附錄) $w_{max} = 1.5(\varepsilon_{s,av} + \varepsilon_{sh})\left\{2\left(c + \frac{s}{10}\right) + k\frac{\phi}{p_e}\right\}$

JSCE-2007 $w_{max} = \left[\frac{\sigma_{se}}{E_s} + \varepsilon'_{csd}\right] 1.1k_1k_2k_3\{4c + 0.7(c_s - \phi)\}$





$\varepsilon_{sh} = 0.002, Avg.\frac{w_{Exp}}{w_{Code}} = 0.87$

$\varepsilon_{sh} = 0.004, Avg.\frac{w_{Exp}}{w_{Code}} = 0.68$

Good prediction generally

Good prediction in low stress

LCSE

Experimental Data

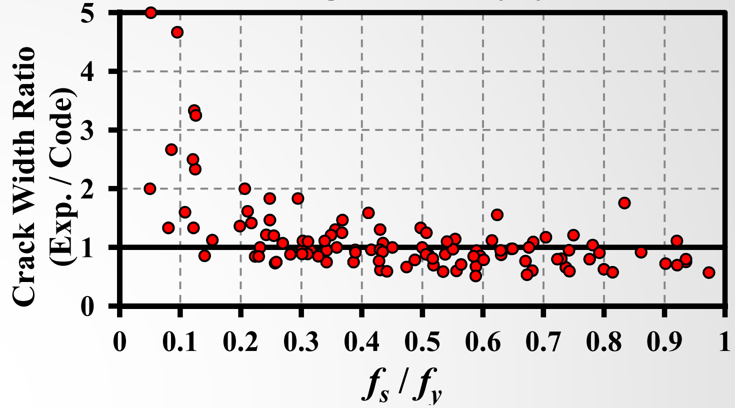
TAIWAN TECH

Flexural Crack-Average Crack Spacing

CEB-FIP

$$w_{max} = (\varepsilon_{sm} - \varepsilon_{cm})(k_3 c + \frac{k_1 k_2 k_4 \phi}{\rho_{p,eff}})$$

CEB-FIP 2010



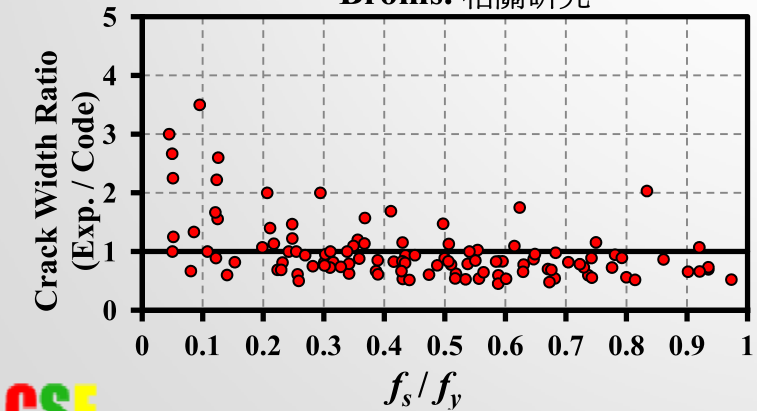
Broms

$$w_{max} = 1.66 \frac{f_s}{E_s} \quad 2d_c$$

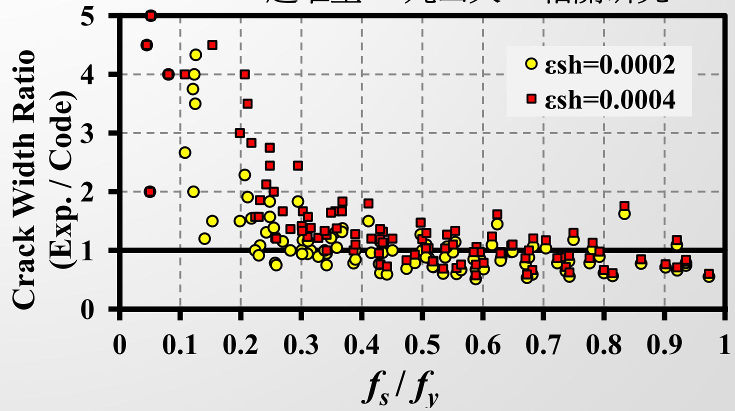
趙唯堅與丸山

$$w_{max} = 1.5\{\frac{\sigma_s}{E_s} - \frac{\sigma_{ctm}}{E_s p_e} - \varepsilon_\phi\} \ \frac{1}{\alpha} k_1 k_2 (4c + 0.7e)$$

Broms. 相關研究



趙唯堅 & 丸山久一 相關研究



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Flexural Crack Control

TAIWAN TECH

Design Formula

Problems：

(1) Low stress level

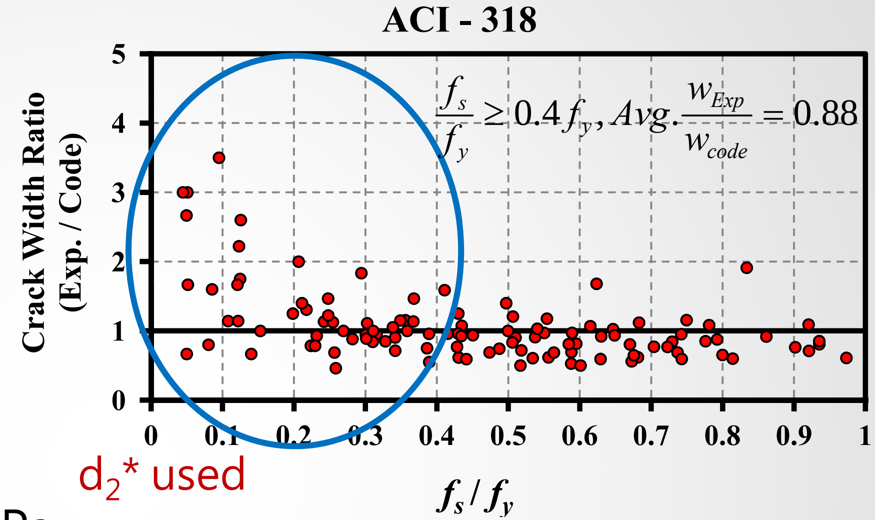
(2) Section parameter

Improving：Crack spacing

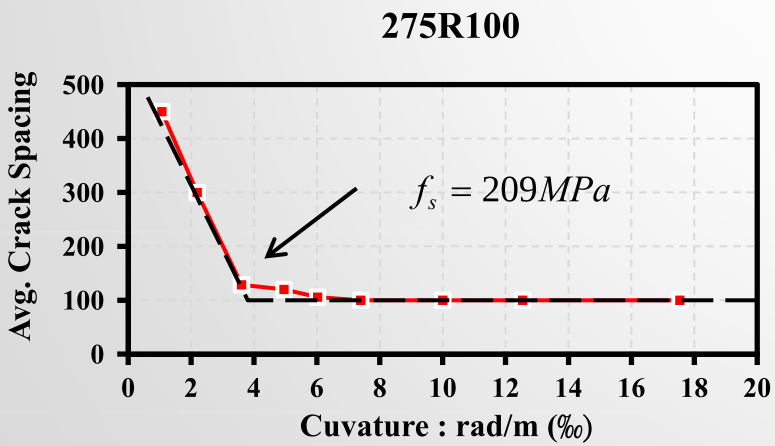
Assumption：

Bi-linear

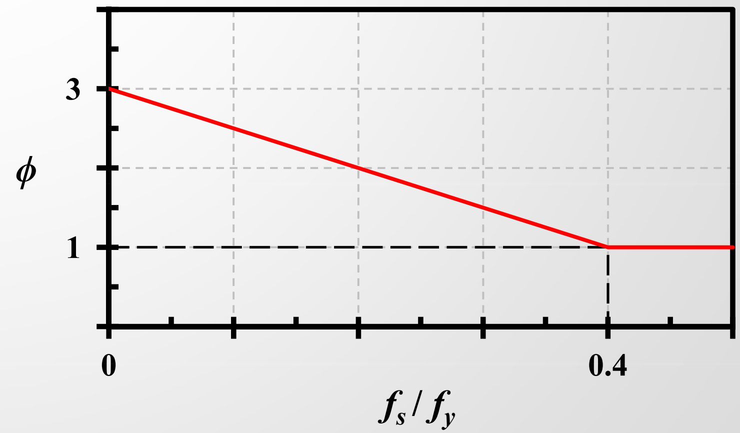
Average stress：263MPa



d_2* used



$\phi = 3 - 5\left(\frac{f_s}{f_y}\right), 0 \leq {}^{f_s}/_{f_y} \leq 0.4$



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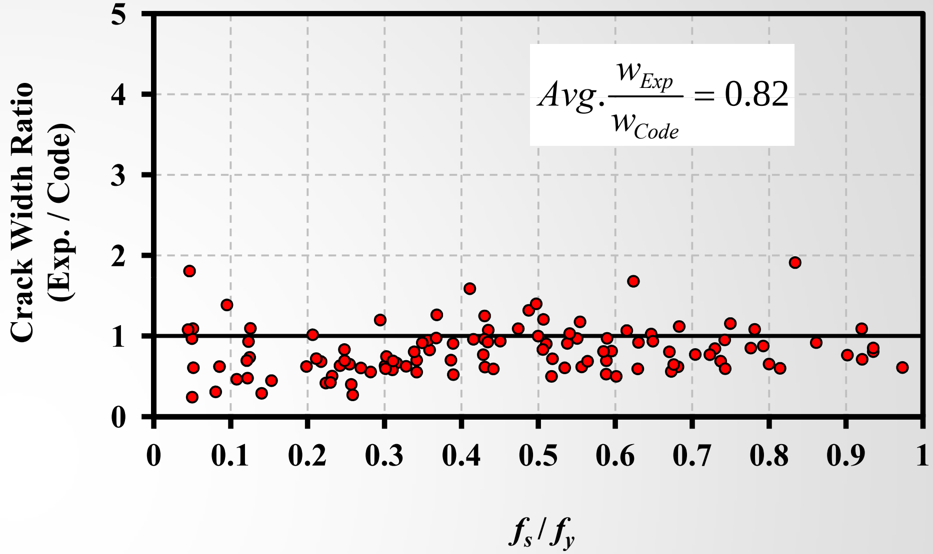
Flexural Crack Control

TAIWAN TECH

Design Formula

Modified



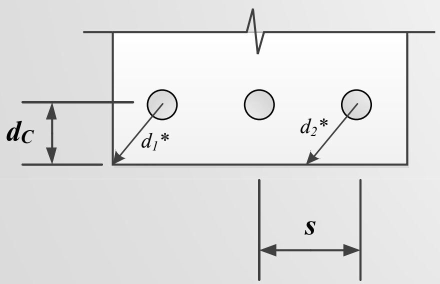
Problems：

(1) Low stress level

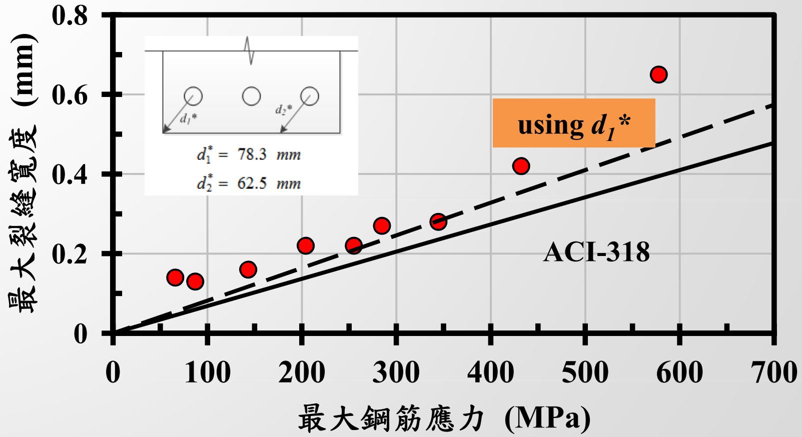
$$w_{max} = \phi \cdot 2\beta \frac{f_s}{E_s}\sqrt{d_c^2 + (\frac{s}{2})^2}$$

$$\phi = 3 - 5(f_s / f_y), 0 \le f_s / f_y \le 0.4$$

(2) Section parameter



$d_2^* \le d_1^*$ ：預測偏低



$$d_2^* \ge d_1^*$$

$$\sqrt{d_c^2 + (\frac{s}{2})^2} \ge \sqrt{d_c^2 + d_c^2}$$

$$s \ge 2d_c$$

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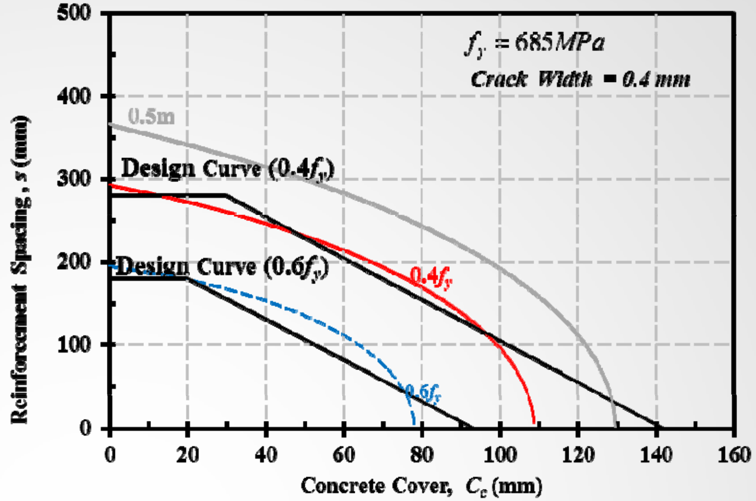
Flexural Crack Control

TAIWAN TECH

Design Formula

$$w_{max} = \phi \cdot 2\beta \frac{f_s}{E_s} \sqrt{d_c^2 + (\frac{s}{2})^2}$$

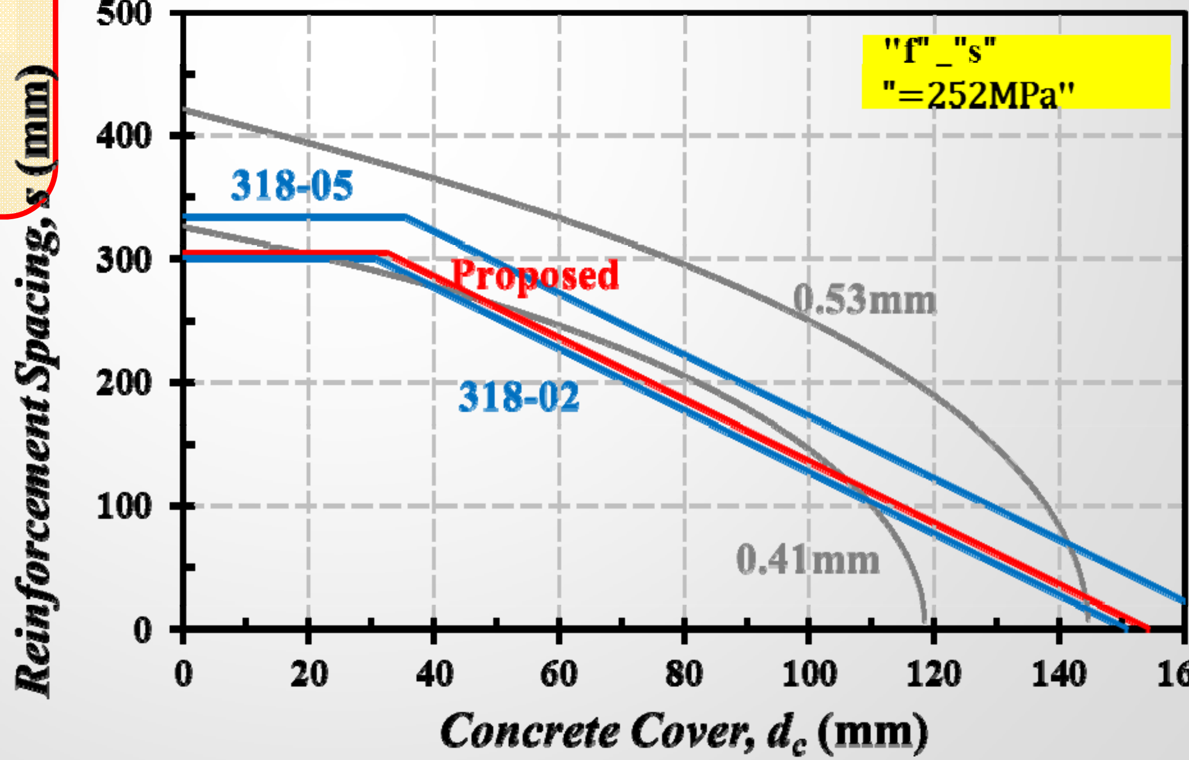
$f_s \geq 0.4 f_y$



Proposed formula

$y = 98.79x$

$$s \leq 280 \frac{274}{f_s}$$



$$s \leq 380 \frac{280}{f_s} - 2.5 c_c$$

$$s \leq 300 \frac{280}{f_s}$$

$f_s \geq 0.4 f_y$

Flexural Crack Control

TAIWAN TECH

手冊建議, 4.3.2

$$s \le 380\frac{280}{f_s} - 2.5C_c \quad s \le \frac{300 \cdot 280}{f_s}$$

f_s為在使用載重下算得之鋼筋應力，若其小於0.4f_y時，須以0.4f_y取代之

[解說] 依現階段之實驗結果可知，梁撓曲裂縫控制可延用ACI318之規定。然而於使用載重下梁之鋼筋應力偏低，則依式計算所得之撓曲裂縫間距會有過小之疑慮，而造成裂縫寬度之計算值亦偏小而不保守；因此，f_s若其小於0.4f_y時，須以0.4f_y代入式，以決定鋼筋中心距s之最大容許值[4]。

[解說] 依ACI318-02可知，式之成立條件為假設鋼筋中心距s之一半會大於撓曲受拉鋼筋中心至最近受拉面之距離，且依現階段之實驗結果可知，若鋼筋中心距s之一半小於撓曲受拉鋼筋中心至最近受拉面之距離時，則依式計算所得之撓曲裂縫間距會有過小之疑慮；因此，本手冊建議鋼筋中心距s之選取不宜小於2C_c[4]。

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Conclusions

TAIWAN TECH

- Shear Crack Control

  Allowable Shear force

$$V_{ser} = \left(\eta_{cr} \times \frac{0.33\sqrt{f_c'}}{1.5} + 0.15\rho_{ts} f_{yt}\right) bd$$

$$V_{rep} = \left(0.27\eta_{cu} \times 0.33\sqrt{f_c'} + 0.20\rho_{ts} f_{yt}\right) bd$$

- Flexural Crack Control

  Spacing of reinforcement

$$s \le 380\left(\frac{280}{f_s}\right) - 2.5c_c$$

$$s \le 300\left(\frac{280}{f_s}\right)$$

$$f_s \ge 0.4 f_y$$

LCSE

Thank you

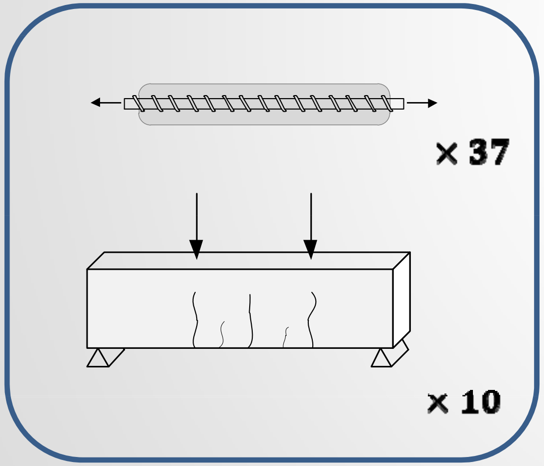
Life-Cycle of
Structure Engineering

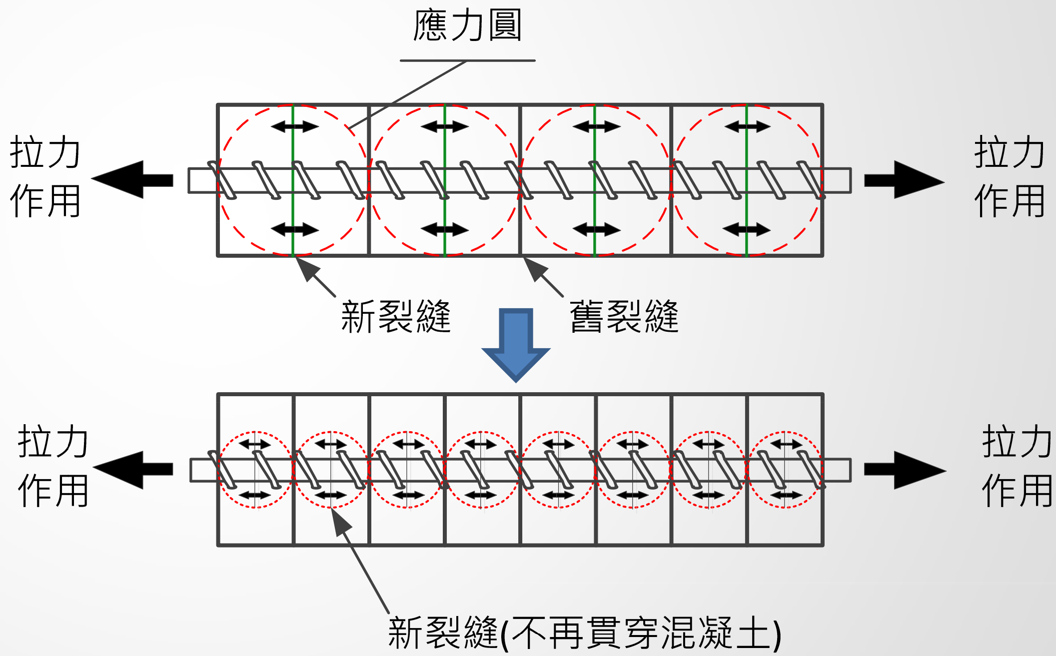
Past Researches

Flexural Crack

Bengt. B. Broms (1965)

Specimens





1.Stable state：140~210MPa
2.Crack spacing：$2d_c$
3.Crack width is proportional to the steel stress

文獻回顧

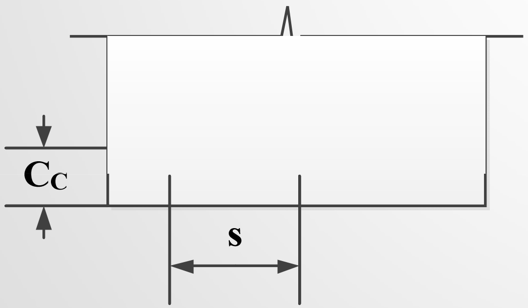
撓曲裂縫發展　**各國撓曲裂縫控制規範**　剪力裂縫控制　損傷評估

美國ACI-318規範　歐洲EuroCode 2規範　日本AIJ-2010附錄　日本JSCE-2007

$$s \le 380\left(\frac{280}{f_s}\right) - 2.5C_c$$

$$s \le 300\frac{280}{f_s}$$

裂縫寬度：0.4mm



不計算裂縫寬度
(1)滿足最小鋼筋量
(2)應力限制
(3)限制鋼筋直徑及間距

$$A_{s,min}\sigma_s = k_c k f_{ct,eff} A_{ct}$$

$$f_s \le 0.75 f_y$$

$$f_c \le 0.6 f'_c$$

鋼筋應力	鋼筋最大間距 (mm)		
(MPa)	w_k=0.4mm	w_k=0.3mm	w_k=0.2mm
160	300	300	200
220	300	250	150
240	250	200	100
280	200	150	50
320	150	100	-
360	100	50	-

鋼筋應力	鋼筋最大直徑 (mm)		
(MPa)	w_k=0.4mm	w_k=0.3mm	w_k=0.2mm
160	40	32	25
220	32	25	16
240	20	16	12
280	16	12	8
320	12	10	6
360	10	8	5
400	8	6	4
450	6	5	-

文獻回顧

撓曲裂縫發展　**各國撓曲裂縫控制規範**　剪力裂縫控制　損傷評估

美國ACI-318規範　歐洲EuroCode 2規範　**日本AIJ-2010附錄**　日本JSCE-2007

裂縫寬度0.3~0.4mm

鋼筋型號	長期容許應力	
	抗壓及抗拉	抗剪
SD295	195	195
SD345	215(*195)	195
SD390	215(*195)	195
SD490	215(*195)	195
SD785	**580**	**580**
*D29以上之鋼筋為()內數值		

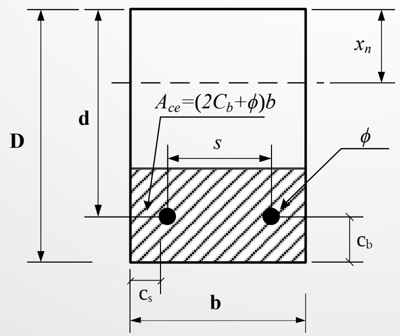
附錄

$$w_{max} = l_{av}\varepsilon_{s,av} + l_{av}\varepsilon_{sh}$$

$$l_{av} = 2\left(c + \frac{s}{10}\right) + k\frac{\phi}{p_e}$$

可適用混凝土抗壓強度

60~100MPa



鋼筋混凝土標準規範

$$w = 1.1k_1k_2k_3\{4c + 0.7(c_s - \phi)\} \times \left[\frac{\sigma_{se}}{E_s} + \varepsilon'_{csd}\right]$$

裂縫寬度限制$\leq 0.3mm$

$$k_2 = \frac{15}{f'_c + 20} + 0.7 \leq 0.9$$

LCSE