1-DAY SEMINAR ON

"PERFORMANCE EVALUATION FOR CONCRETE TO CONCRETE CONNECTION: FROM QUALIFICATION TO DESIGN"

Session 3:

Design Methods:

Rebar End Anchorage Theory, introduction to Bonded Anchor Theory and Strut-and-Tie Design

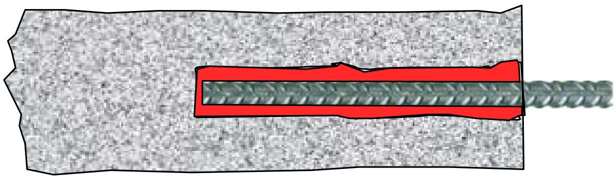
Dr. Daniel Looi
PhD (HKU) | BEng (Malaya)
Lecturer | Swinburne University of Technology (Sarawak Malaysia)
dlooi@swinburne.edu.my

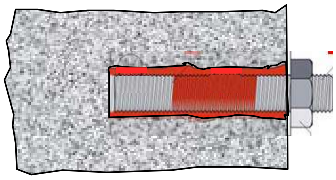
24 September 2019

Content

1. Design philosophy of post-installed rebar (PIR)
2. Design provision for Rebar End Anchorage Theory in EN 1992-1-1 (2004)
3. Introduction to design provision for Bonded Anchor Theory in EN 1992-4 (2018)
4. Introduction to strut-and-tie model
5. Notes on seismic actions
6. Conclusion

1. Design philosophy of post-installed rebar (PIR)





Prequalification:	**EOTA EAD 330087 (2018)**	**EOTA EAD 330499 (2017) (formerly ETAG 001, part 5, 2006)**
Design:	**Design as cast-in rebar end anchorage**	**Design as bonded anchors**
Standards:	**EN 1992-1-1 (2004) or locally MS EN 1992-1-1 (2010)** **(commonly known as EC2)**	**EN 1992-4 (2018)** **(formerly EOTA TR 045, 2013)**

International design standards

Document	Organisation	Roles and functions	Remarks
EN 1992-1-1 (2004) or MS EN 1992-1-1 (2010)	European Committee for Standardization (CEN) or Standards Malaysia	General reinforced concrete design in Europe.	Design provisions for anchorage and splice length in Chapter 8.
ACI 318 (2014)	ACI	General reinforced concrete design in US.	Design provisions for development length (rebar theory) in Chapter 25, and anchor theory in Chapter 17.
EOTA TR 045 (2013)	EOTA	Guideline for design of post-installed anchor theory design in Europe.	Superseded by EN 1992-4 (2018)
EN 1992-4 (2018)	CEN	Standard for design of post-installed anchor theory design in Europe.	
BS 8539 (2012)	The British Standards Institution (BSI)	Selection and installation of post-installed anchors in UK.	Recommendations for anchors without European Technical Approvals (ETAs) qualification.

Comparison of Rebar End Anchorage (REA) theory and Bonded Anchor (BA) theory – 1/4

Main difference	REA theory	BA theory
Prequalification documents	Static action and fire exposure: EOTA EAD 330087 (2018) Seismic action: EAD 331522 (endorsed draft 2018)	Static action: EAD 330499 (2017) Seismic action: EOTA TR 045 (2013)
Design standard	Static action: Chapter 8 in EN 1992-1-1 (2004) or MS EN 1992-1-1 (2010) Seismic action: Chapter 5.6 in EN 1998-1 (2004) or MS EN1998-1 (2015)	EN 1992-4 (2018)

Comparison of Rebar End Anchorage (REA) theory and Bonded Anchor (BA) theory – 2/4

Main difference	REA theory	BA theory
Load transfer mechanism	Equilibrium with local or global concrete struts, may require the supplement of transverse reinforcement in lapping splices.	Utilisation of tensile concrete strength

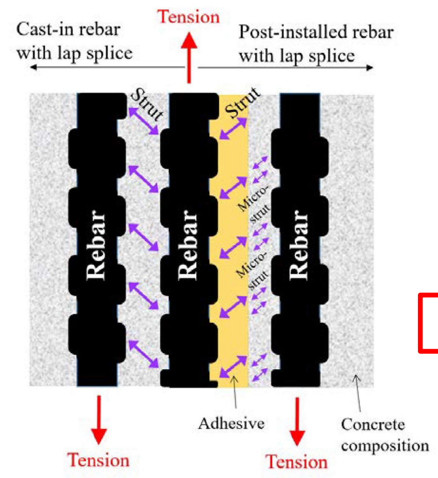


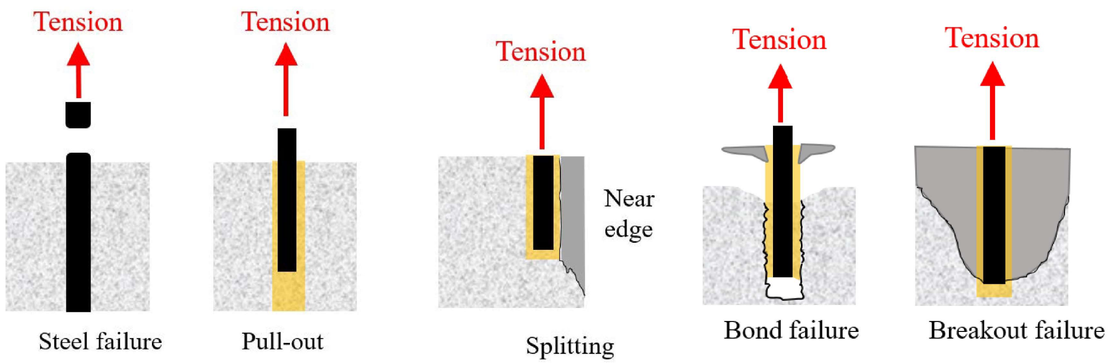
Table 3.1 Strength and deformation characteristics for concrete

	Strength classes for concrete														Analytical relation / Explanation
f_{ck} (MPa)	12	16	20	25	30	35	40	45	50	55	60	70	80	90	
$f_{ck,cube}$ (MPa)	15	20	25	30	37	45	50	55	60	67	75	85	95	105	2.8
f_{cm} (MPa)	20	24	28	33	38	43	48	53	58	63	68	78	88	98	$f_{cm} = f_{ck}+8$(MPa)
f_{ctm} (MPa)	1,6	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1	4,2	4,4	4,6	4,8	5,0	$f_{ctm}=0,30\times f_{ck}^{(2/3)}$ ≤C50/60 $f_{ctm}=2,12\cdot\ln(1+(f_{cm}/10))$ > C50/60
$f_{ctk,0,05}$ (MPa)	1,1	1,3	1,5	1,8	2,0	2,2	2,5	2,7	2,9	3,0	3,1	3,2	3,4	3,5	$f_{ctk;0,05} = 0,7\times f_{ctm}$ 5% fractile

BS EN 1992-1-1:2004
EN 1992-1-1:2004 (E)

Comparison of Rebar End Anchorage (REA) theory and Bonded Anchor (BA) theory – 3/4

Main difference	REA theory	BA theory
Failure modes	<u>Tension</u>: steel failure, pull-out, splitting (near to the edge)	<u>Tension</u>: steel failure, concrete breakout (cone failure), bond failure (pull-out failure), splitting (near to the edge); <u>Shear</u>: steel failure, concrete breakout and concrete pryout



Comparison of Rebar End Anchorage (REA) theory and Bonded Anchor (BA) theory – 4/4

Main difference	REA theory	BA theory
Provision to base material	Uncracked concrete	Cracked and uncracked concrete
Design results	Reinforcement length	Strength capacity
Allowable embedment length (l_b)	max $\{0.3\, l_{b,rqd}; 10\phi; 100\text{ mm}\} \leq l_b \leq 60\phi$ (ϕ is the rebar diameter)	$6\phi \leq l_b \leq 20\phi$ (ϕ is the rebar diameter)

Some latest development for Europe

Engineering Structures 100 (2015) 645–655

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Design of post-installed reinforcing bars as end anchorage or as bonded anchor

Christoph Mahrenholtz *, Rolf Eligehausen, Hans-Wolf Reinhardt

University of Stuttgart, Pfaffenwaldring 4, 70569 Stuttgart, Germany

Some latest development for US

ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title no. 110-S34

Recommended Procedures for Development and Splicing of Post-Installed Bonded Reinforcing Bars in Concrete Structures

by Finley A. Charney, Kamalika Pal, and John Silva

ACI Structural Journal, V. 110, No. 3, May-June 2013.
MS No. S-2011-182.R2 received September 29, 2011, and reviewed under Institute publication policies. Pertinent discussion including author's closure, if any, will be published in the March-April 2014 *ACI Structural Journal* if the discussion is received by November 1, 2013.

Content

2. Design provision for Rebar End Anchorage Theory in EN 1992-1-1 (2004)

■ Longitudinal bar anchorage (Cl. 8.4)

Cl. 8.4.2 (2): Design value of ultimate bond stress, $\boldsymbol{f_{bd} = 2.25\,\eta_1\eta_2 f_{ctd}}$

Where,

Concrete design tensile strength (f_{ctd}) = 5% fractile with consideration of partial safety factor ($f_{ctd} = f_{ctk,0.05}/\gamma_m$);

η_1 and η_2 are to implicitly account for bond condition, position of rebar and rebar diameter.

BS 8110, $f_{bu} = \beta\sqrt{f_{cu}}$

β = 0.5 tens; 0.63 comp for Type 2 deformed bar

Note that β includes γ_m = 1.4

Basic derivation of anchorage length (l_b)

$$F_{bond} \geq F_{rebar}$$

$$f_{bd} \; A_{s,surface} \geq f_{rebar} \; A_s$$

$$f_{bd}(\pi\phi) l_b \geq f_{rebar}\left(\frac{\pi\phi^2}{4}\right)$$

$$l_b \geq \frac{f_{rebar}}{f_{bd}}\frac{\phi}{4}$$

Design yield strength of rebar

$$l_{bd} \geq \frac{0.87 f_{yk}}{f_{bd}}\frac{\phi}{4} \text{ (BS 8110)}$$

Design stress in rebar

$$l_{b,rqd} \geq \frac{\sigma_{sd}}{f_{bd}}\frac{\phi}{4} \text{ (EN 1992-1-1)}$$

Further checking procedure on the design anchorage length (l_{bd})

Bars form (for straight bars, α_1 is 1.0)

Confinement effect

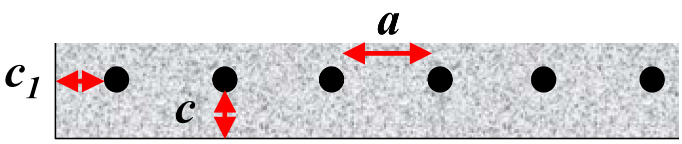
$$l_{bd} = \alpha_1 \alpha_2 \alpha_3 \alpha_5 \, l_{b,rqd} \geq l_{min}$$

- α_2 is a coefficient for the effect of concrete minimum cover to consider splitting failure for straight bars.

$$0.7 \leq \alpha_2 = 1 - \frac{0.15(c_d - \phi)}{\phi} \leq 1.0 \text{ (Tension)}$$

$$\alpha_2 = 1.0 \text{ (Compression)}$$

where $c_d = \min\{a/2, c_1, c\}$ for straight bars, s is the clear spacing of bars, c_1 is the side cover and c is the top or bottom cover.



Splitting failure and α_2

- Splitting is the failure of the concrete surrounding the anchorage because of excessive radial stresses.

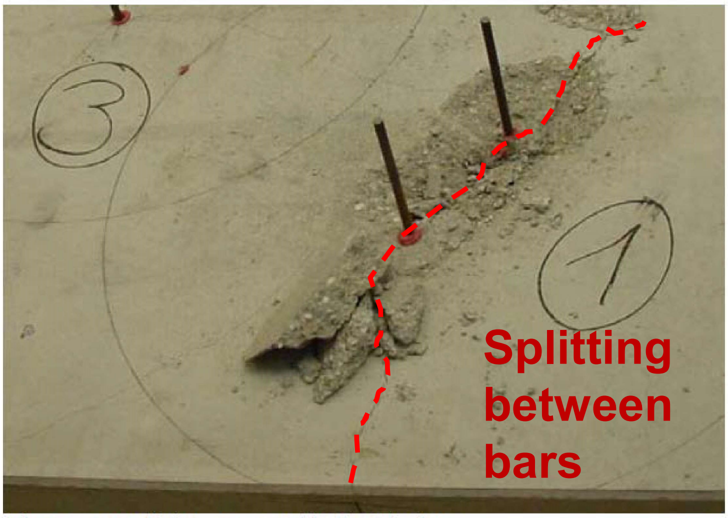
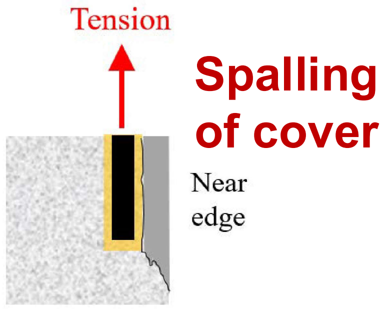


Figure 5: Splitting tests with double bars

Figure taken from:

Randl, N. and Kunz, J (2014), Post-installed reinforcement connections at ultimate and serviceability limit states, Structural Concrete, 15(4), 563-574.



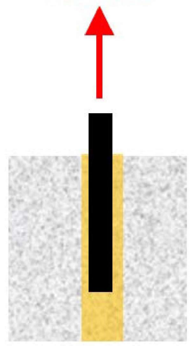
Splitting

Splitting failure and α_2

- Since splitting is a pure concrete failure, the design of post-installed bars should respect the same splitting criteria as cast-in bars.
- As long as $\alpha_2 \geq 0.7$ (correspond to cover $c_d \leq 3\phi$), splitting of concrete cover occurs.
- It should be noted that the case of $\alpha_2 = 1.0$ corresponds to a concrete cover c_d of 1ϕ, which present challenges in hole drilling – need to account for possible deviation in drilling, hence a minimum concrete cover c_d of 2ϕ, corresponds to $\alpha_2 = 0.85$ should be taken.

Splitting failure and α_2

- $\alpha_2 < 0.7$, sufficient concrete cover, rebar will be pulled-out before splitting.
- This is true for EC2 cast-in bars and if bond strength of PIR is the same as cast-in bars.
- Hence, precondition is the use of adhesive with proven strength and stiffness characteristic.
- Bond strength of adhesive agents is given in ETAs of anchors.



What if the bond strength of PIR is proven stronger than cast-in rebar? – an extension of EC2

- Extrapolate α_2 linearly for $c_d \geq 3$, following the approach of Tepfers (1973), hence:
- $\alpha_2 = 1 - \frac{0.15(c_d - \phi)}{\phi}$ in EC2 becomes
- $\alpha_2' = \frac{1}{\frac{1}{0.7} + \delta \frac{c_d - 3\phi}{\phi}} \geq 0.25$
- δ is a factor calibrated by test, if linearly continues with the same slope, $\delta = 0.15$.

Tepfers, R. 1973. A Theory of Bond Applied to Overlapped Tensile Reinforcement for Deformed Bars. Chalmers University, Göteborg. No 73/2.

Summary of bond strength in accordance to REA theory in EN 1992-1-1 (2004)

Concrete characteristic cube strength, $f_{cu,k}$ (MPa)	Concrete characteristic tensile strength at 5% fractile, $f_{ctk,0.05}$ (MPa)	Bond strength (Tension in MPa)				Bond strength (Compression in MPa)	
		BS 8110 (β = 0.5)	EC2 (normalised by α_2 = 0.7)	EC2 (normalised by α_2 = 0.85)	EC2 (normalised by α_2 = 1.0)	BS 8110 (β = 0.63)	EC2 (normalised by α_2 = 1.0)
25	1.5	3.5	4.8	4.0	3.4	4.4	3.4
30	1.8	3.8	5.8	4.8	4.1	4.8	4.1
40	2.1	4.4	6.7	5.5	4.7	5.6	4.7
50	2.5	4.9	8.0	6.6	5.6	6.2	5.6
60	2.9	5.4	9.3	7.7	6.5	6.8	6.5

Note: Material safety factor was excluded

Minimum anchorage length ($l_{b,min}$)

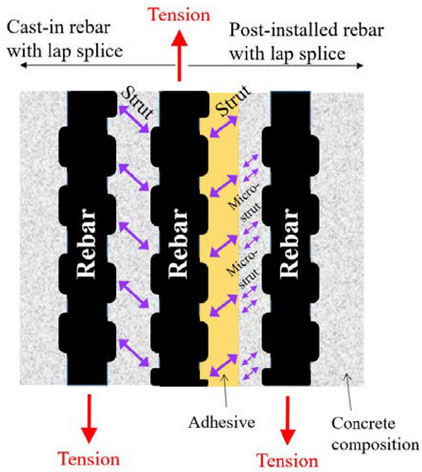
$$l_{b,min} \geq \max\{0.3l_{b,rqd}, 10\phi, 100\ mm\}\ \text{(Tension)}$$

$$l_{b,min} \geq \max\{0.6l_{b,rqd}, 10\phi, 100\ mm\}\ \text{(Compression)}$$

It should be noted that the minimum anchorage length (l_{min}) shall be multiplied by an amplification factor (α_{lb}) to account for the difference of cast-in place and post-installed rebar in cracked concrete. In general, if there is no test carried out to post-installed rebars in cracked concrete in accordance to qualification document EOTA EAD 330087 (2018), α_{lb} is taken as 1.5.

Lapped splice (l_o)

$$l_o = \alpha_1 \alpha_2 \alpha_3 \alpha_5 \alpha_6 l_{b,rqd} \geq l_{o,min}$$

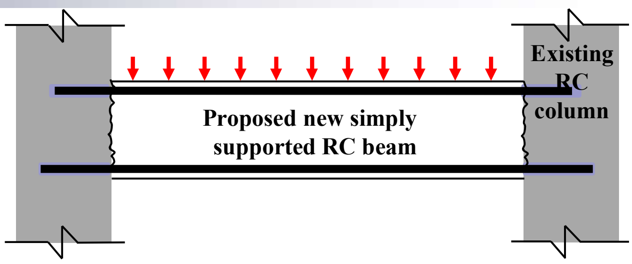


Where, α_6 is a coefficient of percentage of lapped bar (p_1) relative to total cross-section area within $0.65 l_o$ from the centre of the lap length

$1.0 \leq \alpha_6 = (\rho_1/25)^{0.5} \leq 1.5$

$$l_{o,min} \geq \max\{0.3\alpha_6\, l_{b,rqd}, 15\phi, 200 \text{ mm}\}$$

Other rules



Cl. 9.2.1.2(1) and Cl. 9.2.1.4(1):

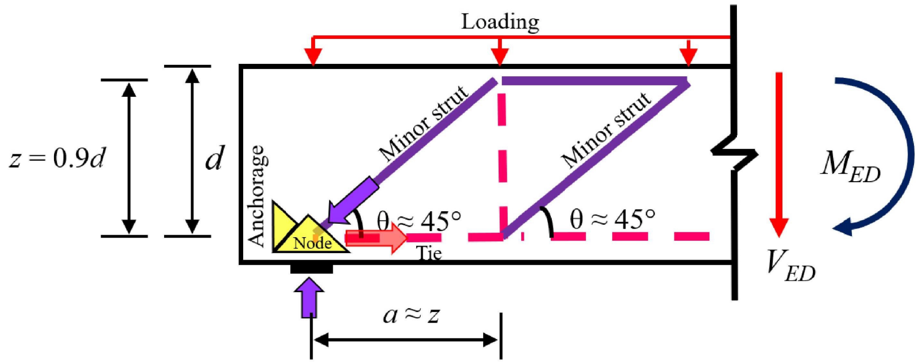
Simply supported beam

- Values of 15% of maximum bending moment in the span and 25% (National Annex dependent, in contrast, it is 50% in BS 8110) of the steel area provided in the span is recommended for top and bottom reinforcement, respectively, at the support of simply supported beam.

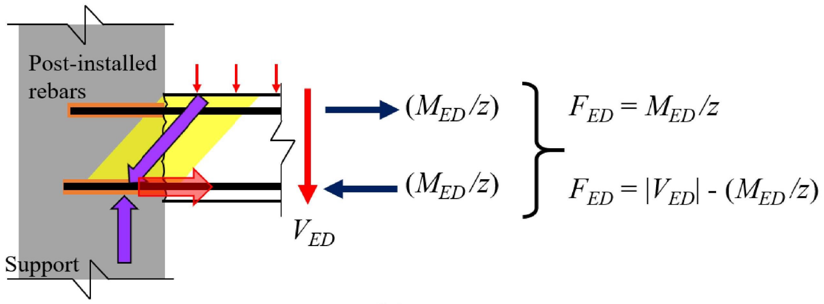
- Both top and bottom steel are to be anchored with l_{bd}, measured from the face of support. It is interesting to note that Cl. 9.2.1.4(2) allows a strut-and-tie equivalent model to calculate the axial forces in the rebar, which appears to be more suitable for the design stress (σ_{sd}) estimation in $l_{b,rqd} \geq \frac{\sigma_{sd}}{f_{bd}} \frac{\phi}{4}$

Cl. 9.2.1.4(2)

- Similar to Strut-and-Tie (without axial force)

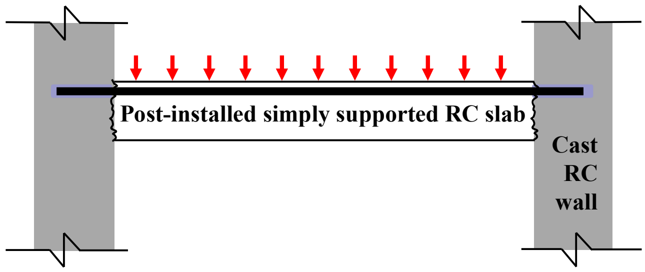


(a)



(b)

Other rules



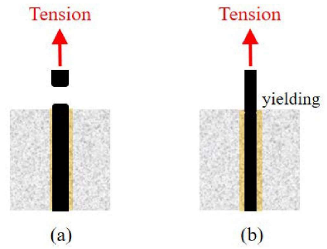
Cl. 9.3.1.2: **Simply supported solid slab**

- In simply supported slab, 15% (for end support) to 25% (intermediate support) of maximum bending moment in the span and 50% of the calculated span reinforcement should be provided for the top and bottom bar at the support of solid slab, respectively (as opposed to the 50% provision in BS 8110).
- Both top and bottom steel are anchored with l_{bd}, measured from the face of support. Similar for simply supported beam, Cl. 9.2.1.4(2) of the strut-and-tie model is allowed.

Content

1. Design philosophy of PIR
2. Design provision for Rebar End Anchorage Theory in EN 1992-1-1 (2004)
3. Introduction to design provision for Bonded Anchor Theory in EN 1992-4 (2018)
4. Introduction to strut-and-tie model
5. Notes on seismic actions
6. Conclusion

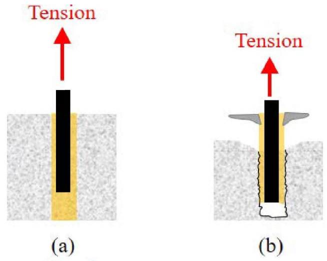
3. Introduction to BA Theory in EN 1992-4 (2018)



Steel failure (Cl. 6.2.2)

$N_{Rd,s} = f_{uk}A_s/\gamma_{Ms}$ where $\gamma_{Ms} = 1.2 \;\; f_{uk}/f_{yk} \geq 1.4$

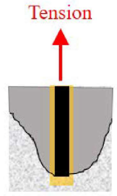
$N_{Rd,y} = f_{yk}A_s/\gamma_s$ where $\gamma_s = 1.15$



Combined bond (pull-out) and concrete failure (Cl. 6.2.2)

$$N^{\circ}_{Rk,p} = f_{bd} \;\pi\; \phi \;\; l_b$$

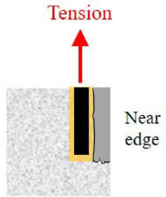
$$N_{Rk,p} = N^{\circ}_{Rk,p} \;\; \psi_{A,Np} \;\; \psi_{s,Np} \;\; \psi_{g,Np} \;\; \psi_{re,N} \;\; \psi_{ec,Np}$$



Concrete cone (breakout) failure (Cl. 6.2.3)

$$N^{\circ}_{Rk,c} = k_{cr} \;\sqrt{f_{cu}} \;\; l_b{}^{1.5}$$

$$N_{Rk,c} = N^{\circ}_{Rk,c} \;\; \psi_{A,Nc} \;\; \psi_{s,N} \;\; \psi_{re,N} \;\; \psi_{ec,N}$$



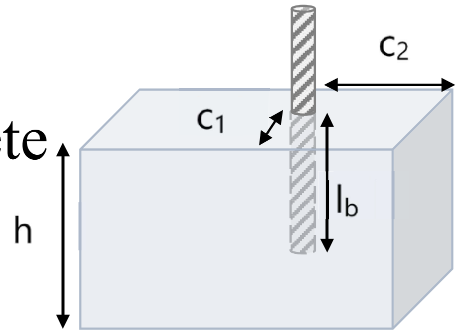
Splitting failure (Cl. 6.2.4)

$$N_{Rk,sp} = N^{\circ}_{Rk,c} \;\; \psi_{A,Nsp} \;\; \psi_{s,Nsp} \;\; \psi_{re,N} \;\; \psi_{ec,N} \;\; \psi_{h,sp}$$

$$N_{Rd} = \min\{N_{Rd,s};\; N_{Rd,y};\; N_{Rk,p}/\gamma_{Mp};\; N_{Rk,c}/\gamma_{Mc};\; N_{Rk,sp}/\gamma_{Msp}\}$$

An example output of BA theory - 1/4

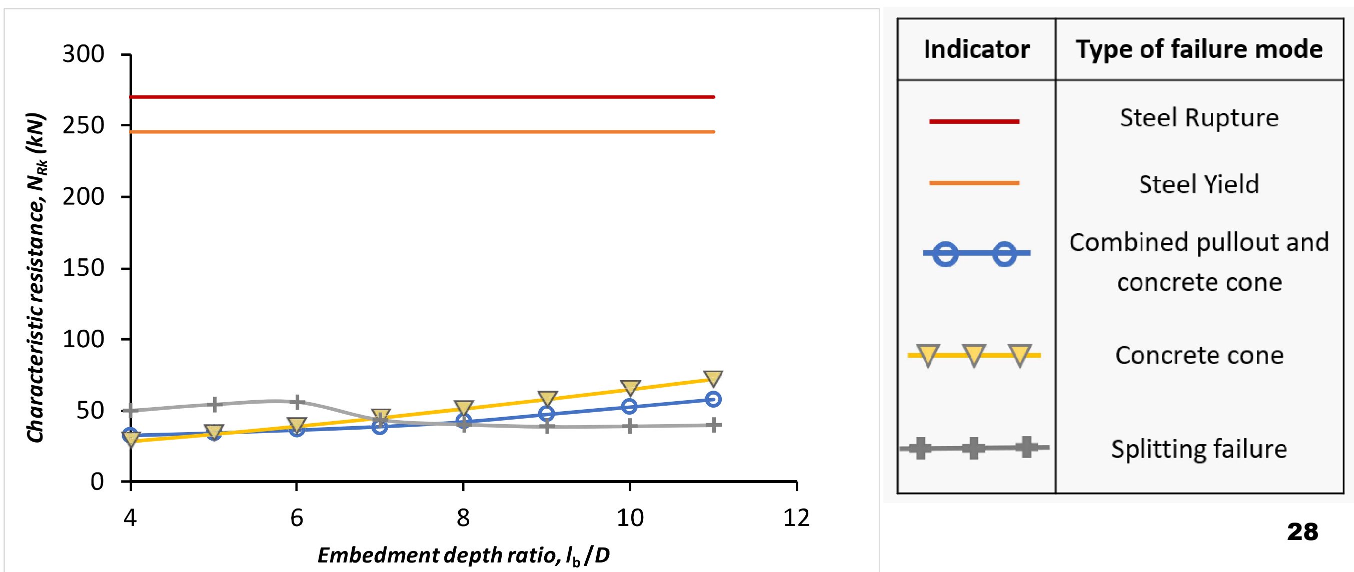
- T25 rebar
- 300 mm thick cracked concrete
- C50/60
- c_d = 75 mm
- Adhesive RE500 V3



Acknowledgment: The computation work of BA theory was done by ***Ms. Eva Wong Shu Wen****, graduate of Swinburne University (Sarawak)*

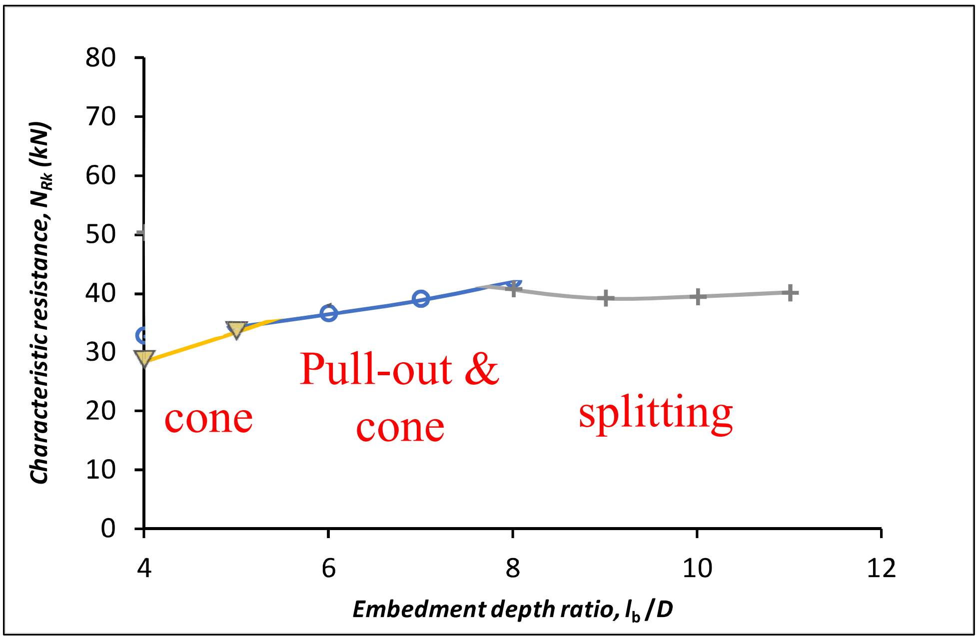
An example output of BA theory - 2/4

l_b/D	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
$N_{Rd,s}$ (kN)	269.98	269.98	269.98	269.98	269.98	269.98	269.98	269.98	269.98	269.98	269.98	269.98	269.98	269.98	269.98	269.98	269.98
$N_{Rd,y}$ (kN)	245.44	245.44	245.44	245.44	245.44	245.44	245.44	245.44	245.44	245.44	245.44	245.44	245.44	245.44	245.44	245.44	245.44
$N_{Rk,p}$ (kN)	32.75	34.40	36.53	38.92	42.29	47.57	52.86	58.15	63.43	68.72	74.00	79.29	84.58	89.86	95.15	100.44	105.72
$N_{Rk,c}$ (kN)	28.52	33.49	38.96	44.83	51.07	57.64	64.50	71.66	79.09	86.79	94.73	102.92	111.34	119.99	128.87	137.96	147.25
$N_{Rk,sp}$ (kN)	50.20	54.67	56.28	43.79	40.59	39.04	39.42	40.13	40.83	41.53	42.21	42.88	43.54	44.17	44.80	45.41	46.01



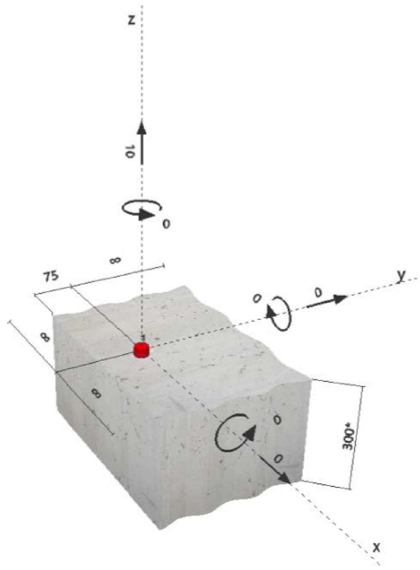
An example output of BA theory - 3/4

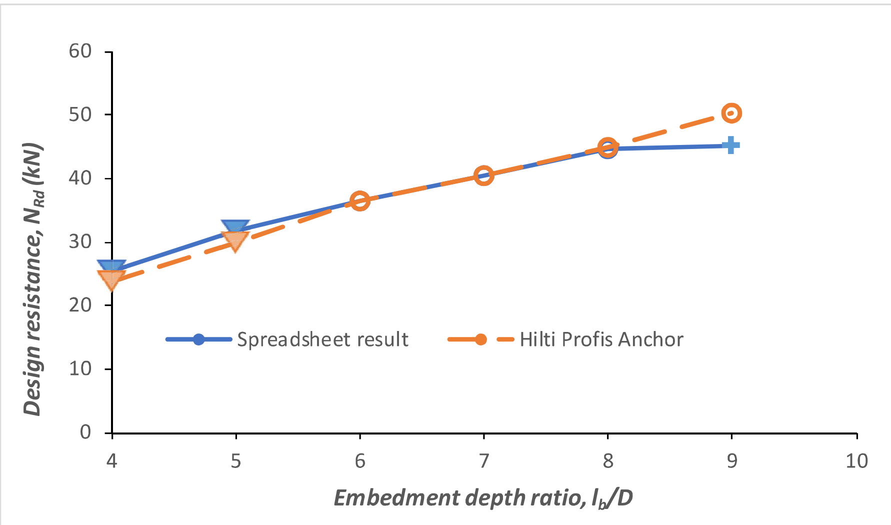
- Take the lower bound envelope



An example output of BA theory - 4/4

- Check with Hilti Profis Anchor

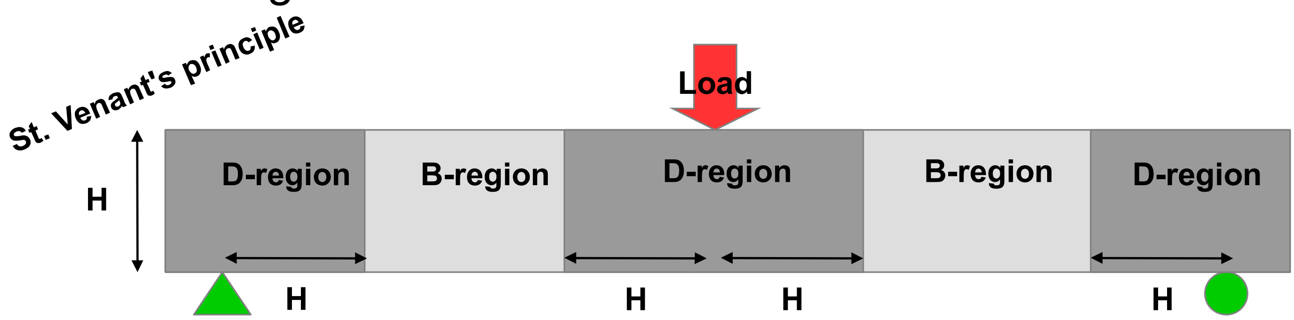




Content

4. Introduction to Strut-and-Tie Method (STM)

The D-region in STM



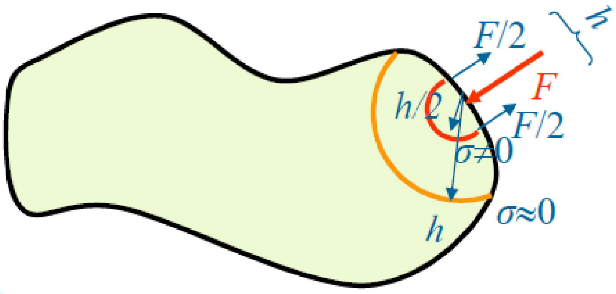
Where D = Disturbed or Discontinued (complex stress field); B = Bernoulli (linear strain, plane section remains plane)

Brief history and background:

- Schlaich et al. (1987), Collins and Mitchell (1991), MacGregor (1992), Foster and Gilbert (1996), Tjhin and Kuchma (2002)
- Lower bound plastic theory (equilibrium and yield criteria for rigid perfectly plastic) – modified with efficiency factor v, and crushing of concrete does not happen prior to yield of rebars

St. Venant principle

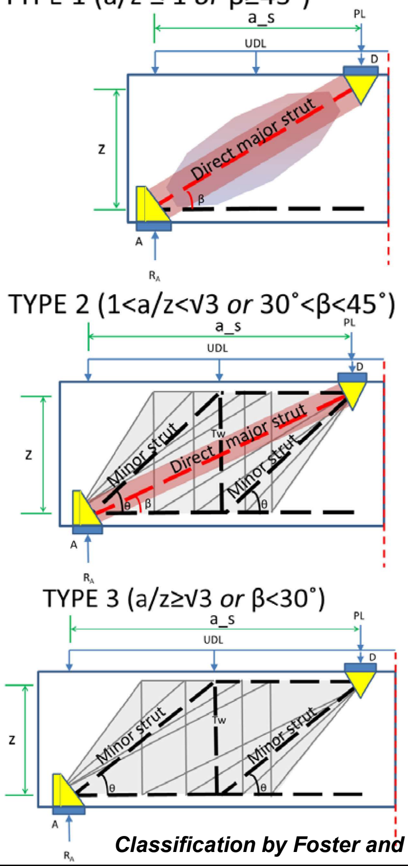
- The localized effects caused by any load acting on the body will dissipate or smooth out within regions that are sufficiently away from the location of the stress concentration



Zone of body affected by self equilibrium forces applied to surface

The "strut"

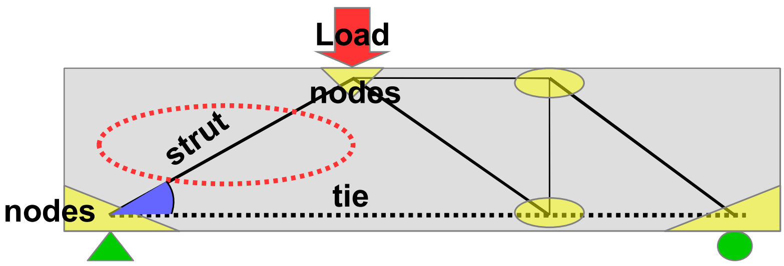
TYPE 1 (a/z ≤ 1 *or* β≥45˚)

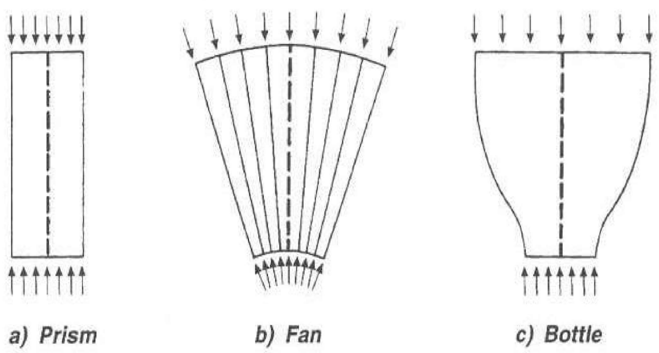


TYPE 2 (1<a/z<√3 *or* 30˚<β<45˚)

TYPE 3 (a/z≥√3 *or* β<30˚)

Classification by Foster and Gilbert (1996)

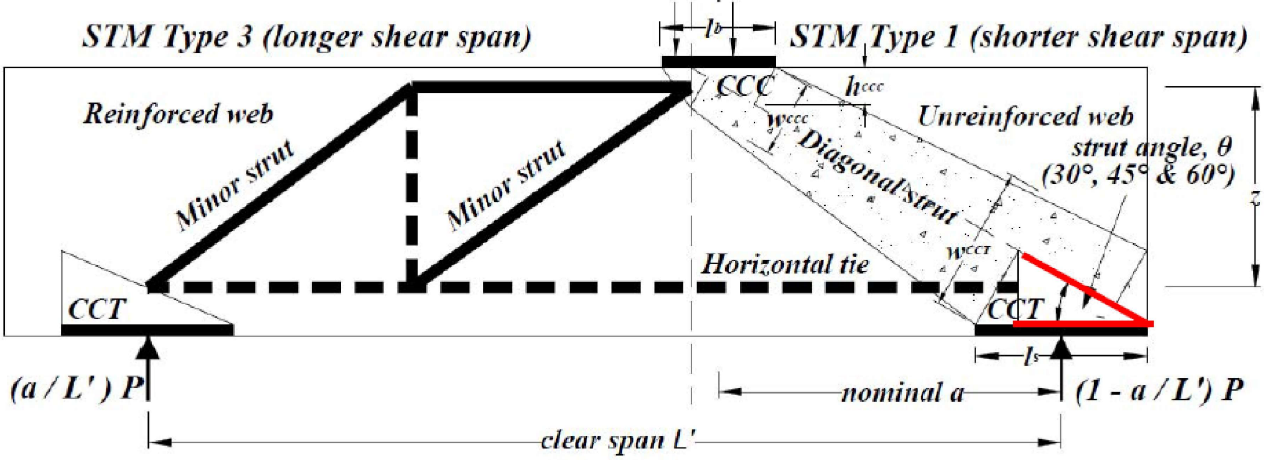




Three Types of Struts (Adapted from Schlaich et al 1987)

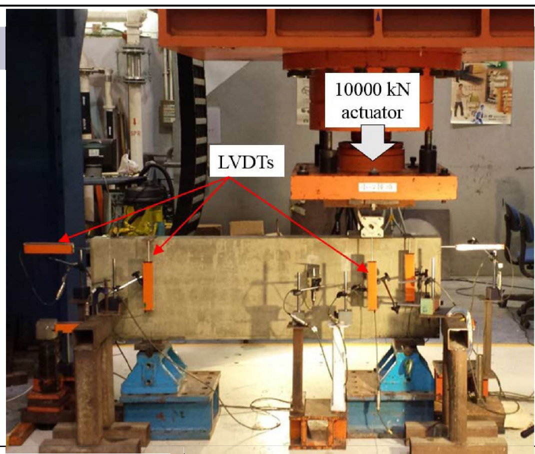
Experiment on strength of strut

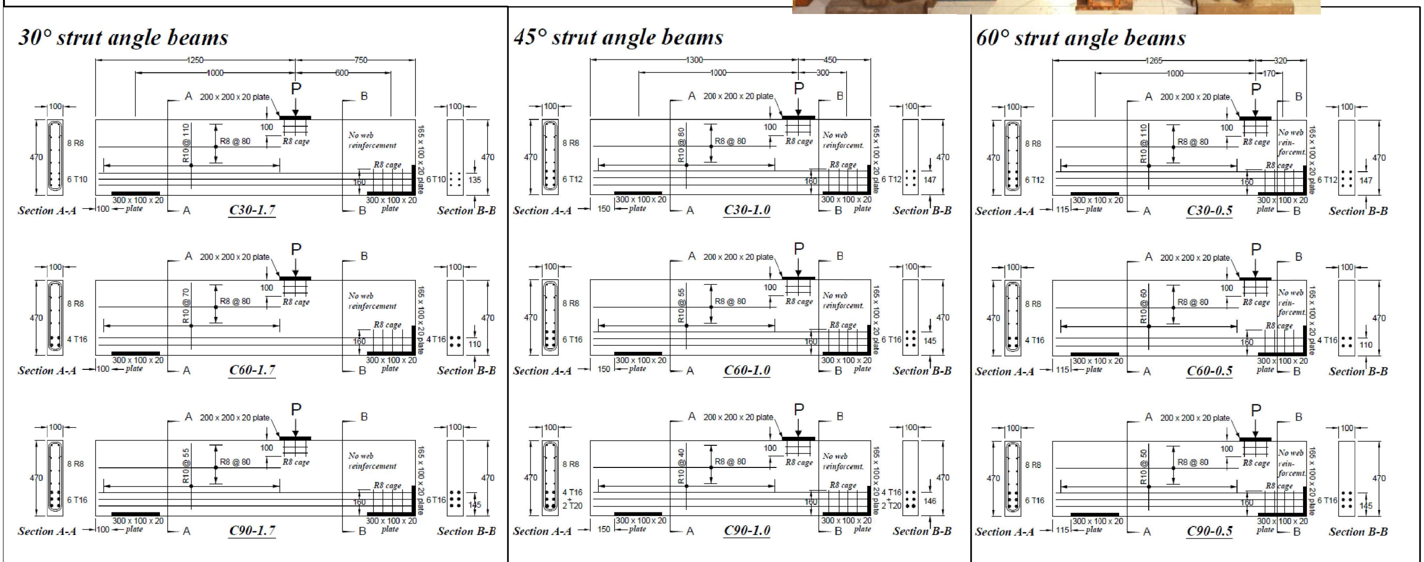
*R.K.L. Su and **D.T.W Looi** (2016), Revisiting the unreinforced strut efficiency factor, ACI Structural Journal, **113**(2), p301-312.*



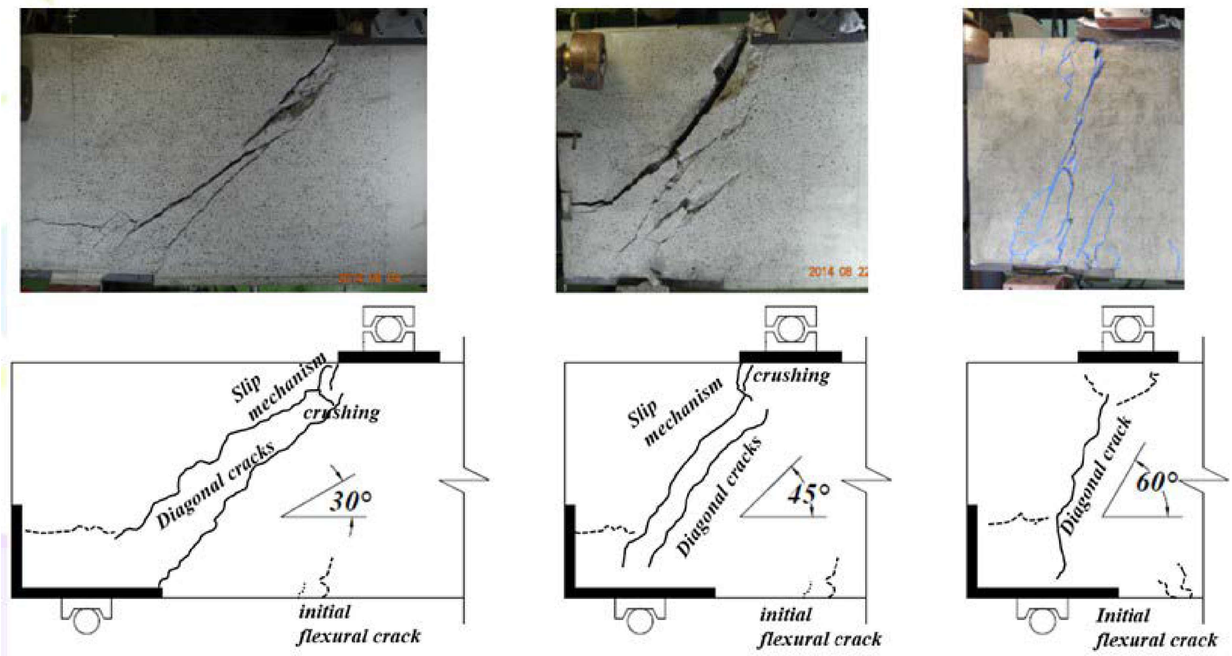
- Varying strut angles (30°, 45° & 60°) OR *a/d* (1.73, 1.0, 0.5)
- Varying concrete strength (30 MPa, 60 MPa and 90 MPa)

Experiment matrix



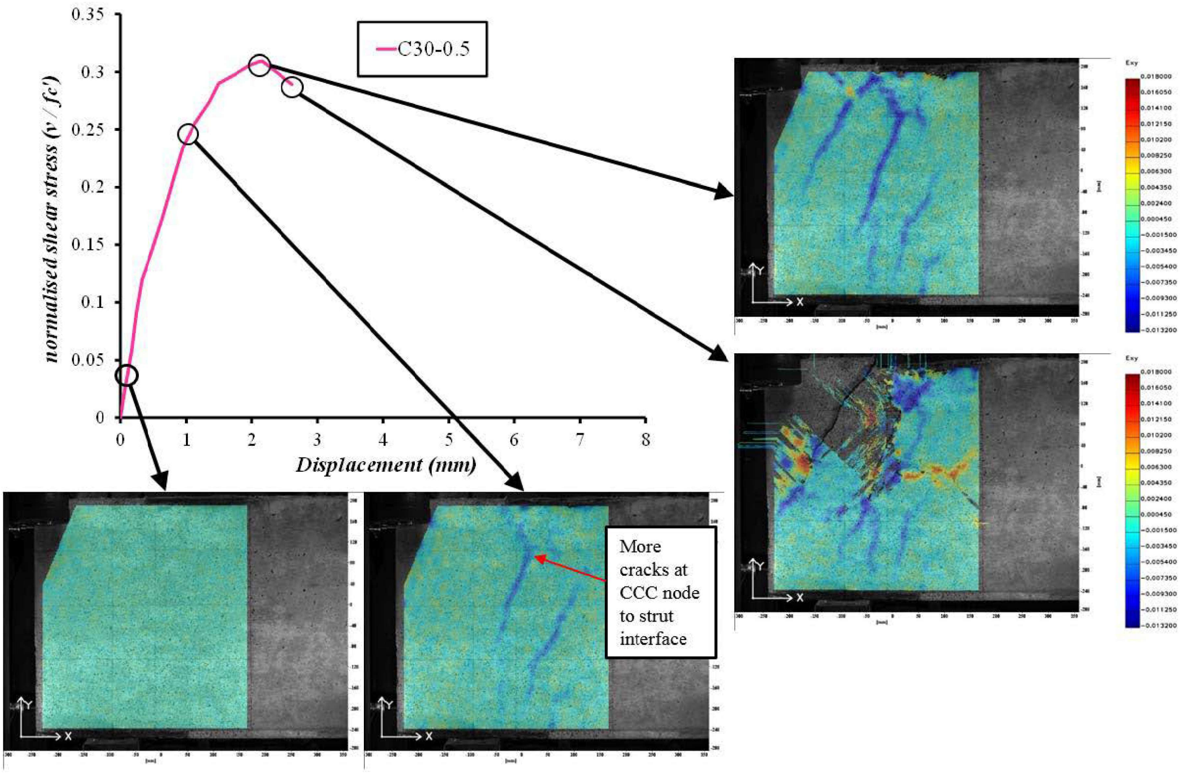


Typical failure mode of strut



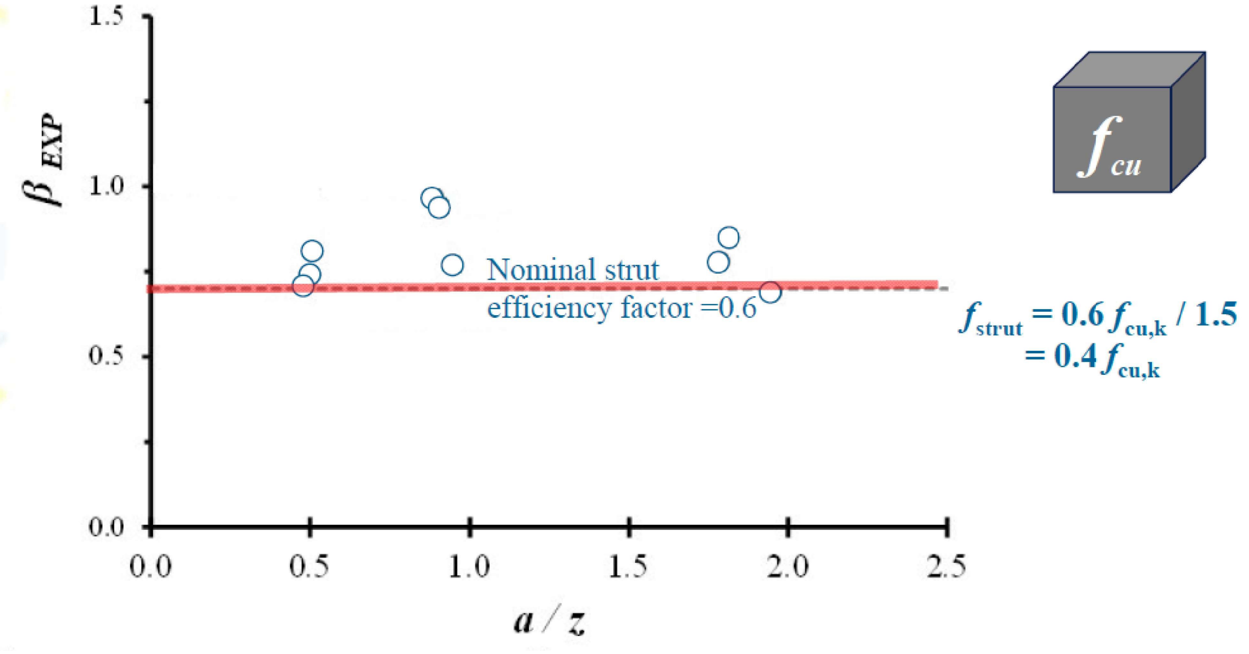
30° strut angle *45° strut angle* *60° strut angle*

Failure of strut



Strut strength

- The strut efficiency factor is found to be 0.6.



Strut strength in EN 1992-1-1 (2004)

- $\sigma_{Rd,max} = 0.6\, v' f_{cd}$

- Recommended strut efficiency factor in EC2 is $v' = 1 - f_{ck} / 250$

- Compared to Su and Looi (2015), $v' = 0.6$

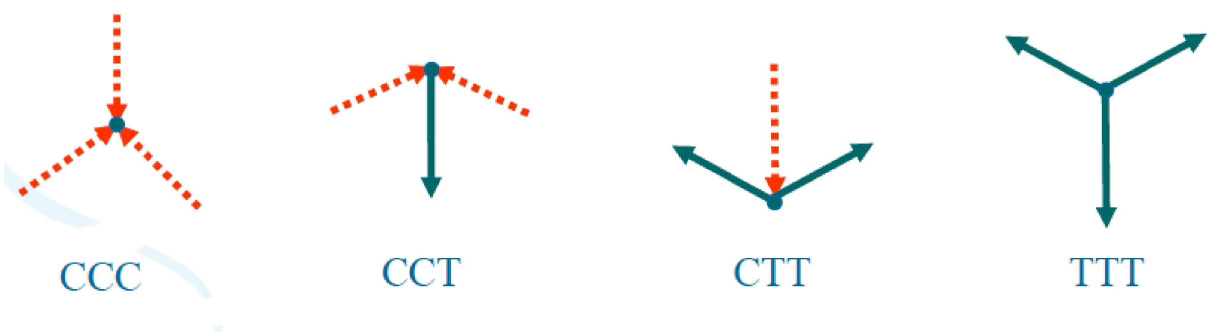
The “ties”

- Design strength of steel ties, $f_{yd} = f_{yk}/1.15$
- Reinforcement should be anchored into nodes
- The anchorage may start as the bar enters the strut

The “nodes”

- Nodes are the connections of struts and ties in truss models

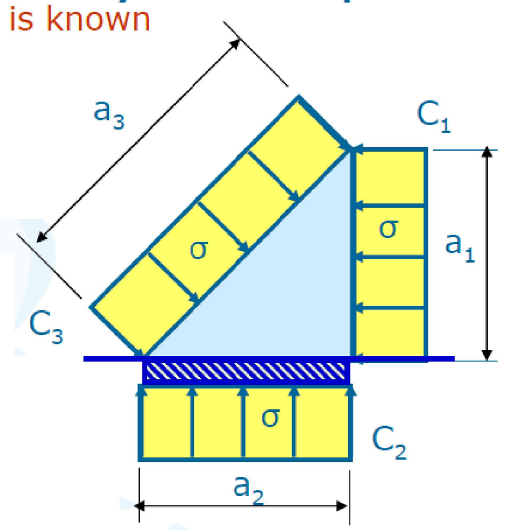
Type of nodes



Equilibrium of nodes

Node in Hydrostatic Equilibrium

a_2 is known



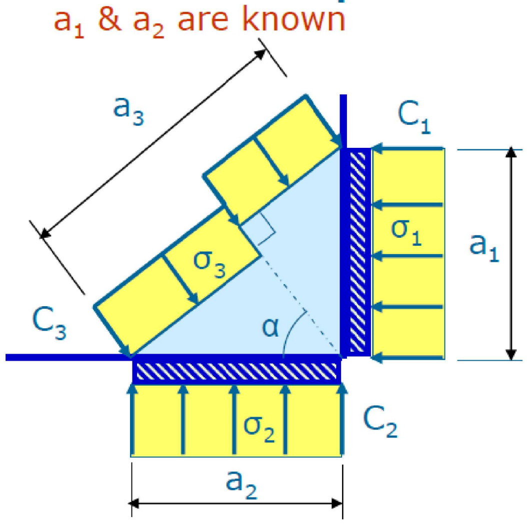
force → size of node →

$$\frac{C_3}{a_3} = \frac{C_2}{a_2} = \frac{C_1}{a_1} = \sigma \times b$$

$$a_1 = \frac{a_2}{C_2} C_1$$

Node in Force Equilibrium

a_1 & a_2 are known

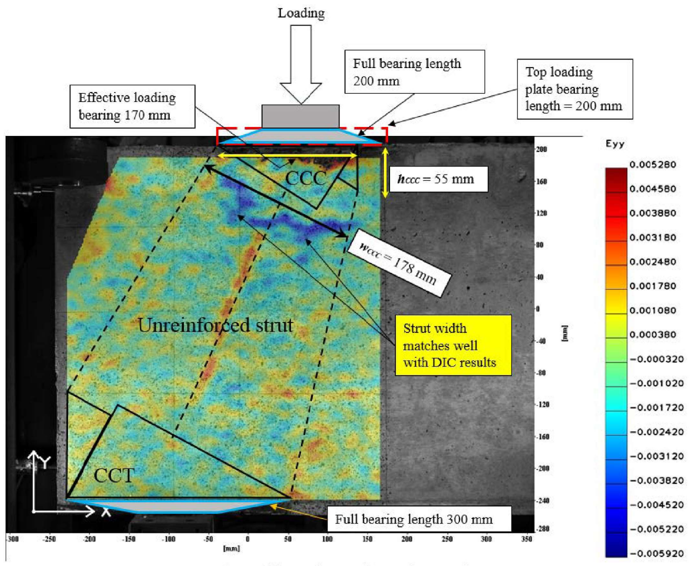


$$C_3 = (C_1^2 + C_2^2)^{1/2}$$

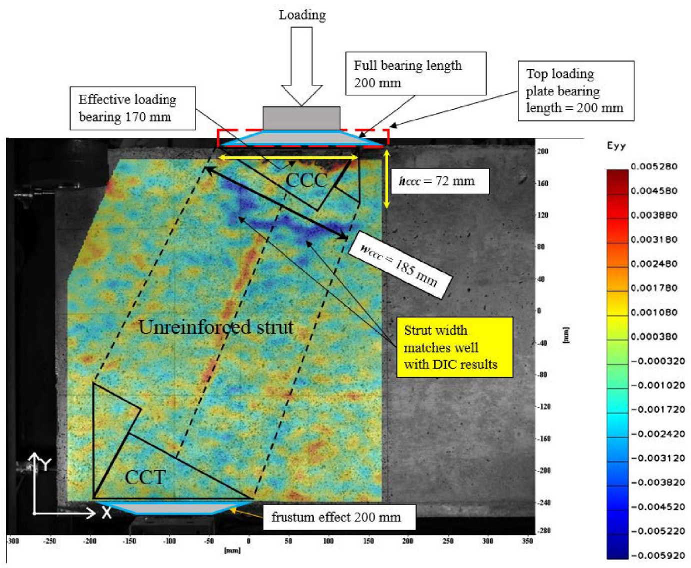
$$a_3 = a_1 \cos\alpha + a_2 \sin\alpha$$

$$\sigma_3 = C_3 / (a_3 \times b)$$

Bearing size affects the node size – 1/2

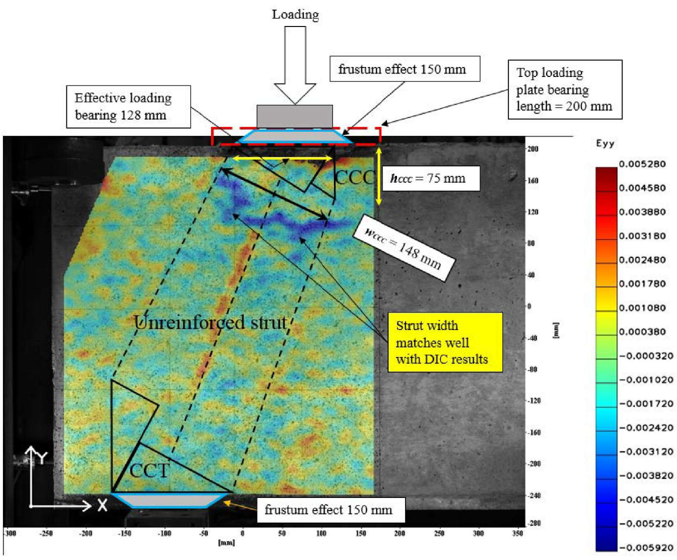


(a) 200 mm loading bearing length with full bearing support

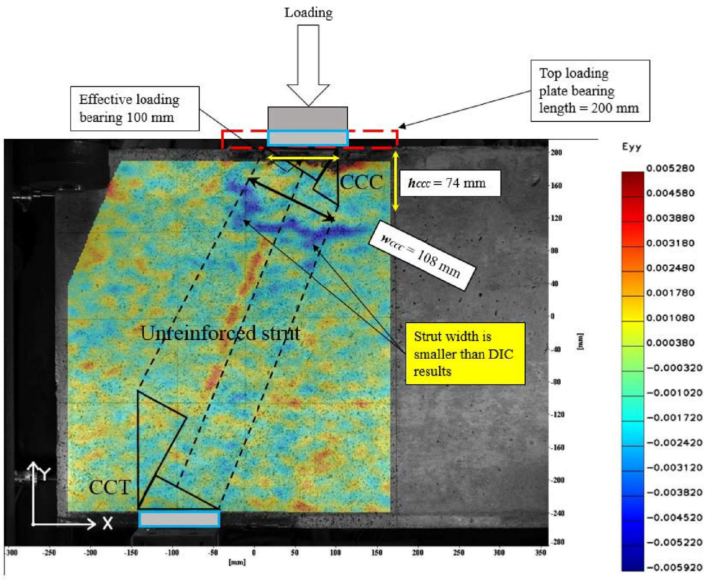


(b) 200 mm bearing length

Bearing size affects the node size – 2/2



(c) 150 mm bearing length



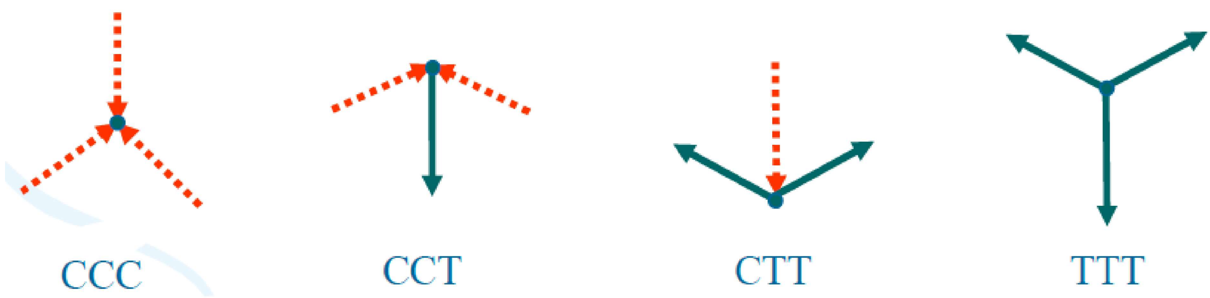
(d) 100 mm bearing length

*Su RKL, **Looi DTW** (2017): Reply to discussion on "Revisiting the unreinforced strut efficiency factor", ACI Structural Journal, 114(1), 291-293.*

Node strength in EN 1992-1-1 (2004)

- CCC: $\sigma_{Rd,max} = k_1\ v'\ f_{cd}$, $k_1 = 1.0$ by NA
- CCT: $\sigma_{Rd,max} = k_2\ v'\ f_{cd}$, $k_2 = 0.85$ by NA
- CTT: $\sigma_{Rd,max} = k_3\ v'\ f_{cd}$, $k_3 = 0.75$ by NA

Type of nodes



Some applications of STM

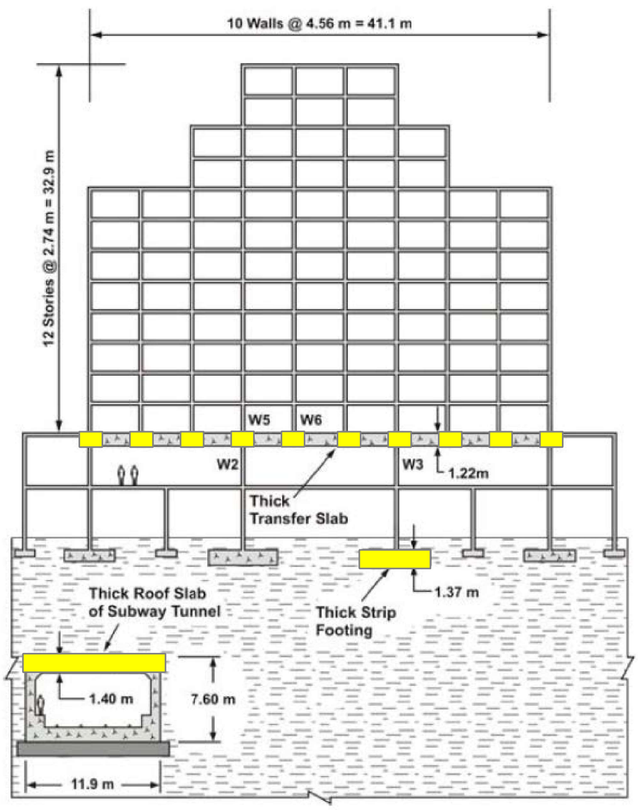
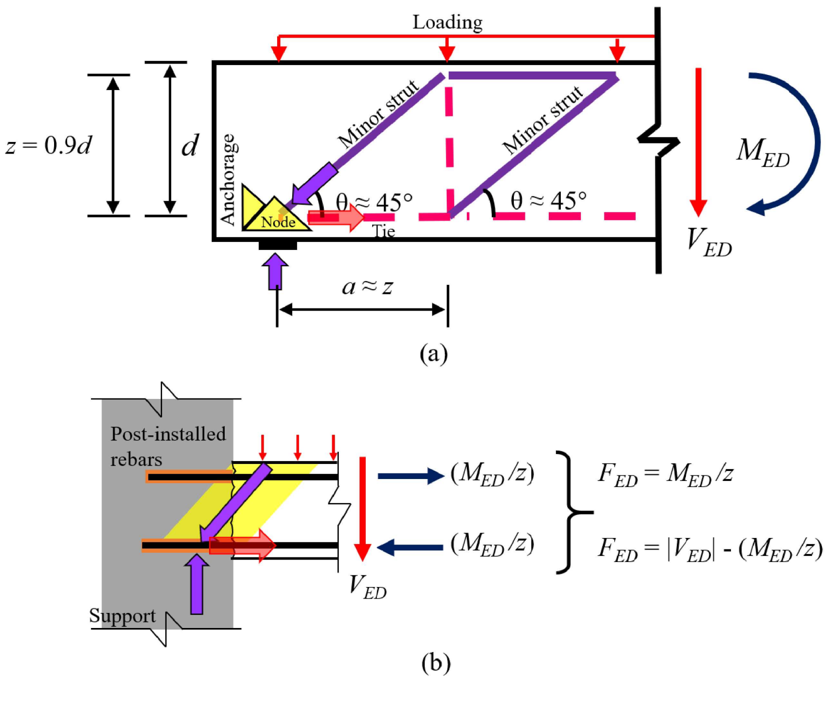


Figure taken from:

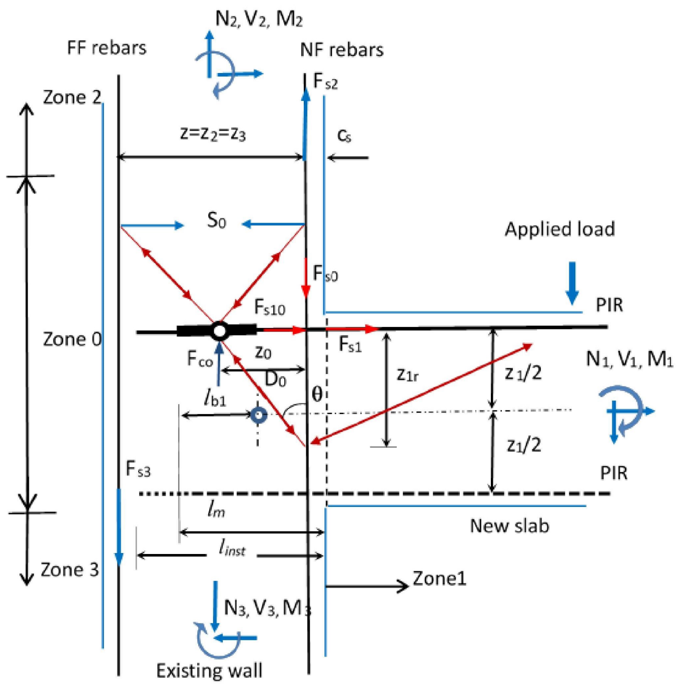
Collins et. al. (2007), Morley Symposium on Concrete Plasticity and its Application. University of Cambridge

Relevance of STM to PIR in simply supported application



R.K.L. Su, ***D.T.W Looi*** *and Y.L. Zhang (in press, 2019), Guide for Design, Installation and Assessment of Post-installed Reinforcement, HKU Press, Hong Kong.*

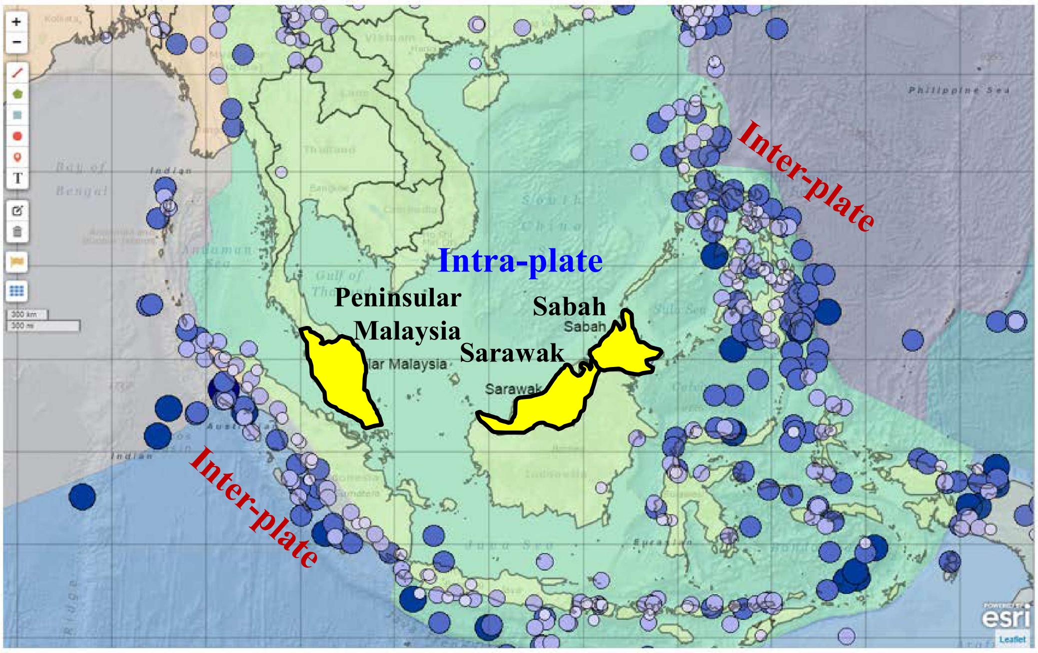
Relevance of STM to PIR in moment joint application (state-of-the-art)



A.Y.F. Lee, R.K.L. Su and Ricky W.K. Chan (2019). Structural behaviour of post-installed reinforcement bars in moment connections of wall-slabs, Engineering Structures, 195, 536-550.

Content

General seismic environment of Malaysia



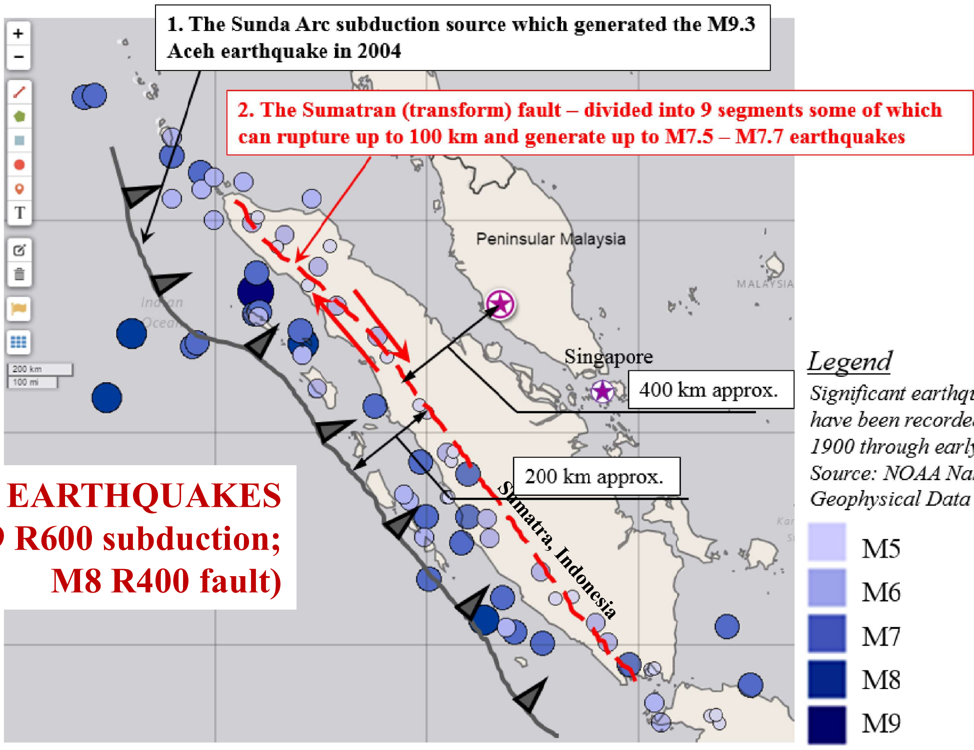
Legend

Significant earthquakes that have been recorded from 1900 through early 2014. Source: NOAA National Geophysical Data Center.

- M5
- M6
- M7
- M8
- M9

http://mapmaker.nationalgeographic.org/dFhAVtrGc8lfOt8SXUNWnv/?edit=eVJPruTexDKnLZwb4E7jU6

Peninsular Malaysia (inter-plate)



DISTANT EARTHQUAKES (M9 R600 subduction; M8 R400 fault)

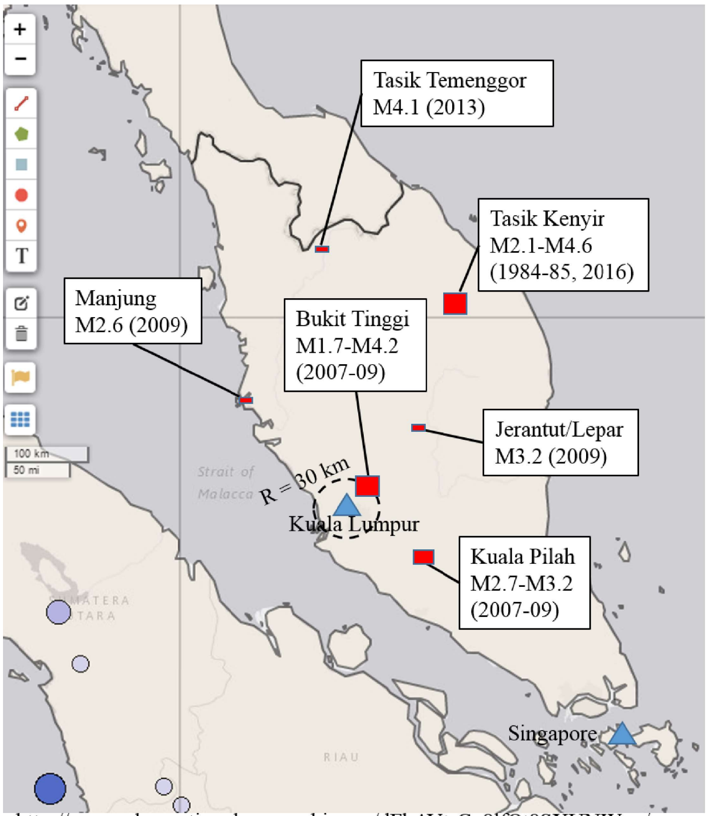
Legend

Significant earthquakes that have been recorded from 1900 through early 2014. Source: NOAA National Geophysical Data Center.

- M5
- M6
- M7
- M8
- M9

http://mapmaker.nationalgeographic.org/dFhAVtrGc8lfOt8SXUNWnv/?edit=eVJPruTexDKnLZwb4E7jU6

Peninsular Malaysia (intra-plate)

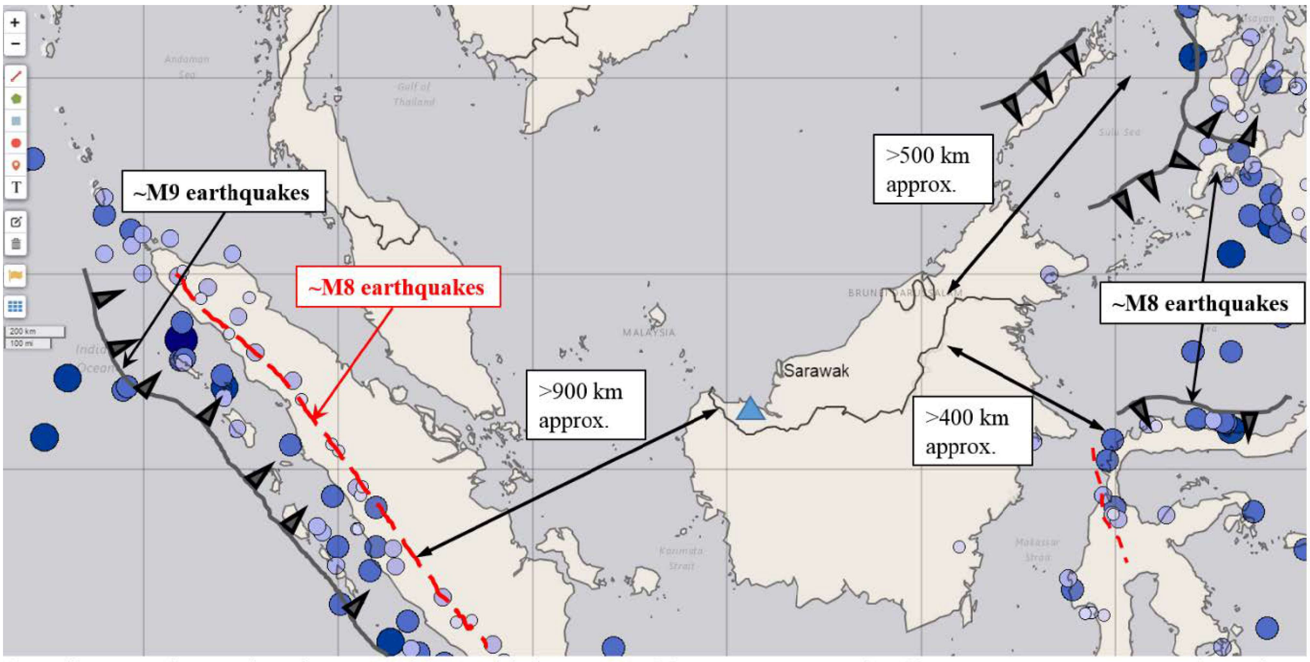


http://mapmaker.nationalgeographic.org/dFhAVtrGc8lfOt8SXUNWnv/?edit=eVJPruTexDKnLZwb4E7jU6

Sporadic LOCAL EARTHQUAKES

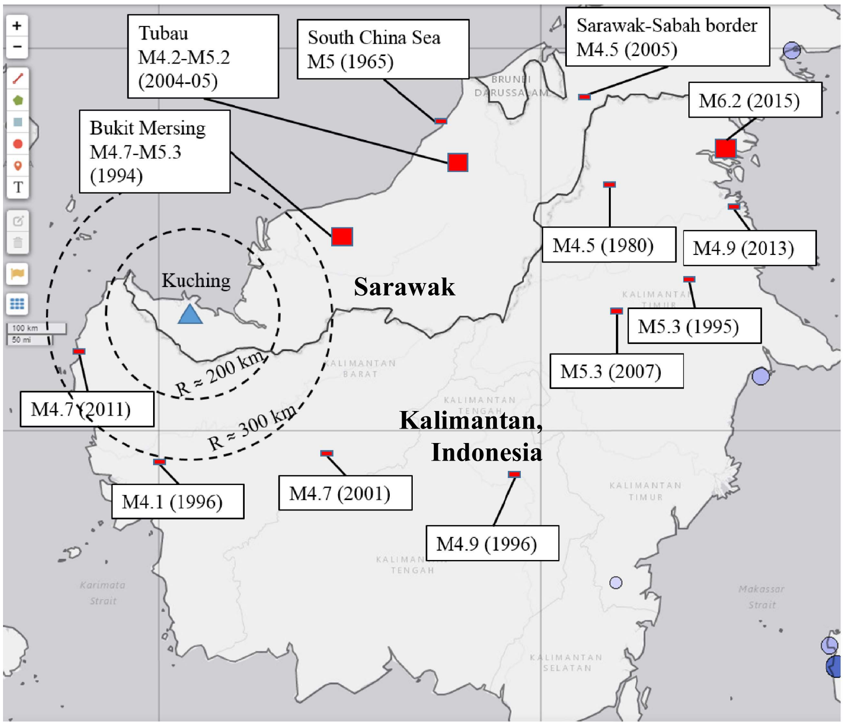
Sarawak (inter-plate)

DISTANT EARTHQUAKES (>400 km)



http://mapmaker.nationalgeographic.org/dFhAVtrGc8lfOt8SXUNWnv/?edit=eVJPruTexDKnLZwb4E7jU6

Sarawak (intra-plate)

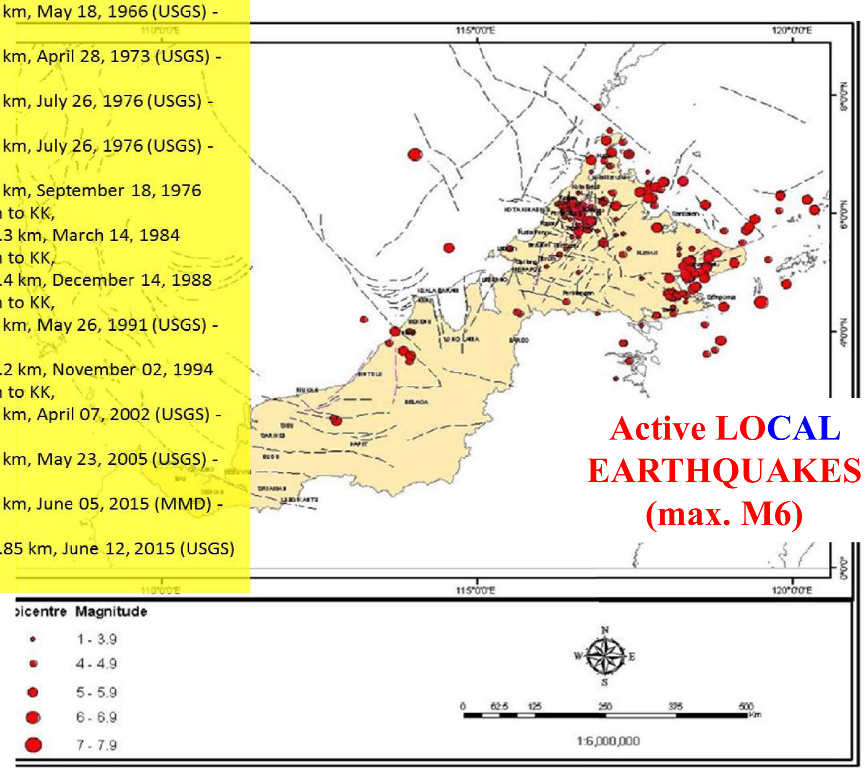


http://mapmaker.nationalgeographic.org/dFhAVtrGc8lfOt8SXUNWnv/?edit=eVJPruTexDKnLZwb4E7jU6

Sporadic LOCAL EARTHQUAKES (max. M5)

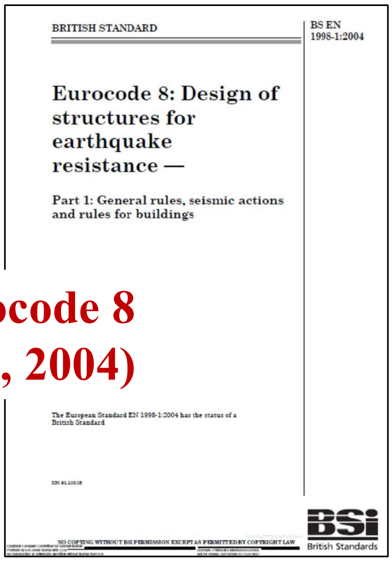
Sabah (inter-plate & intra-plate)

M5.3, depth 33 km, May 18, 1966 (USGS) - 70 km to KK,
M5.4, depth 33 km, April 28, 1973 (USGS) - 185 km to KK,
M5.3, depth 33 km, July 26, 1976 (USGS) - 250 km to KK,
M6.2, depth 33 km, July 26, 1976 (USGS) - 270 km to KK,
M5.0, depth 33 km, September 18, 1976 (USGS) - 264 km to KK,
M5.6, depth 50.3 km, March 14, 1984 (USGS) - 270 km to KK,
M5.1, depth 79.4 km, December 14, 1988 (USGS) - 197 km to KK,
M5.1, depth 33 km, May 26, 1991 (USGS) - 70 km to KK,
M5.7, depth 55.2 km, November 02, 1994 (USGS) - 300 km to KK,
M5.1, depth 33 km, April 07, 2002 (USGS) - 175 km to KK,
M5.3, depth 19 km, May 23, 2005 (USGS) - 180 km to KK,
M5.9, depth 10 km, June 05, 2015 (MMD) - 60 km to KK,
M5.3, depth 11.85 km, June 12, 2015 (USGS) -60 km to KK.



Active LOCAL EARTHQUAKES (max. M6)

The documents



BRITISH STANDARD

BS EN 1998-1:2004

Eurocode 8: Design of structures for earthquake resistance —

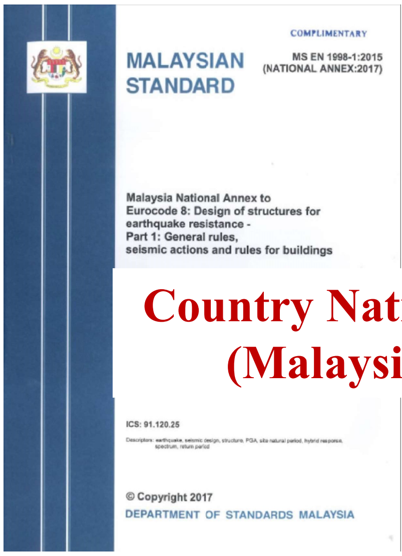
Part 1: General rules, seismic actions and rules for buildings

The European Standard EN 1998-1:2004 has the status of a British Standard

NO COPYING WITHOUT BSI PERMISSION EXCEPT AS PERMITTED BY COPYRIGHT LAW

BSI British Standards

Main Eurocode 8 (EC8, 2004)



COMPLIMENTARY

MALAYSIAN STANDARD

MS EN 1998-1:2015 (NATIONAL ANNEX:2017)

Malaysia National Annex to Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings

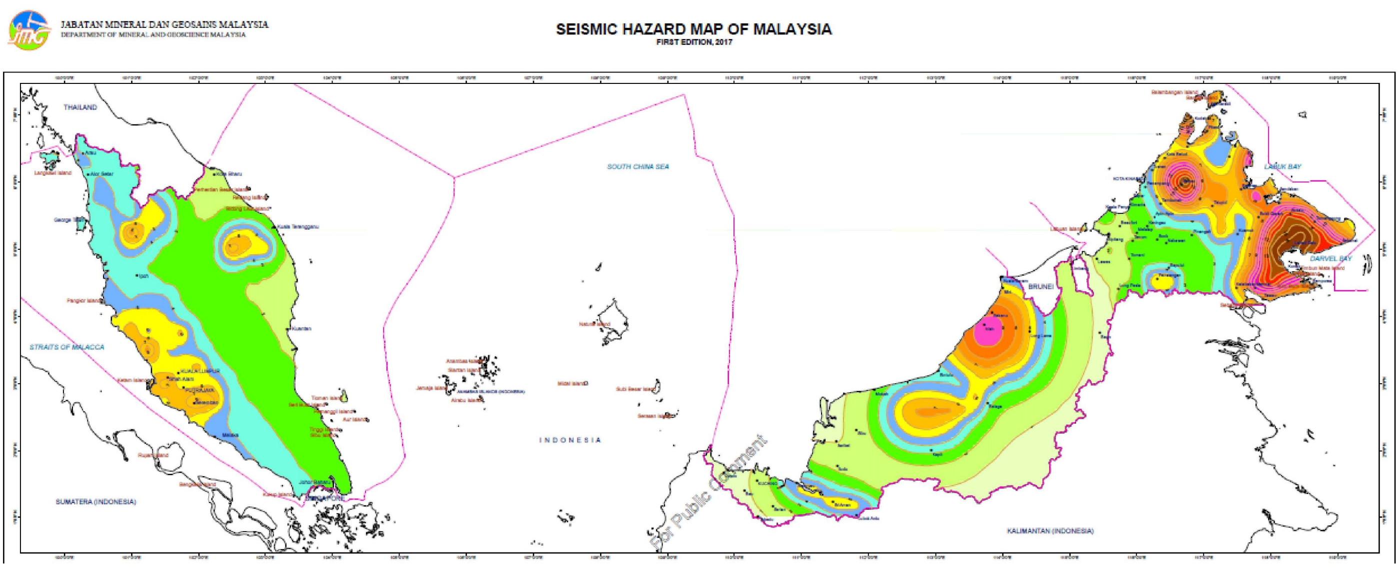
ICS: 91.120.25

© Copyright 2017

DEPARTMENT OF STANDARDS MALAYSIA

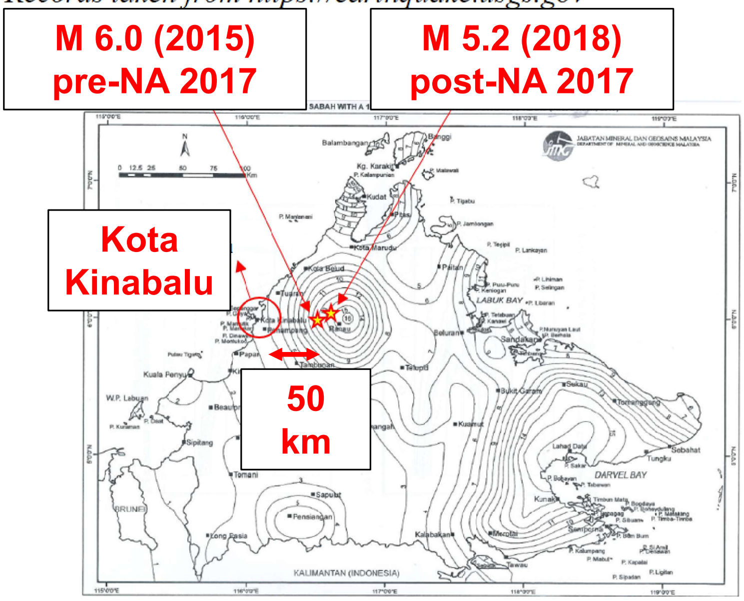
Country National Annex (Malaysia NA, 2017)

Hazard map (please exercise extreme caution)



Consequence of uncontrolled use of PSHA

Records taken from https://earthquake.usgs.gov

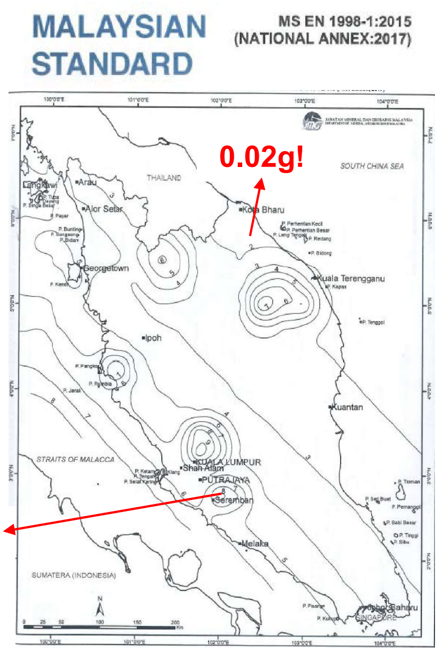


(a) Enacted version in National Annex (2017)

<u>Consequence</u>:

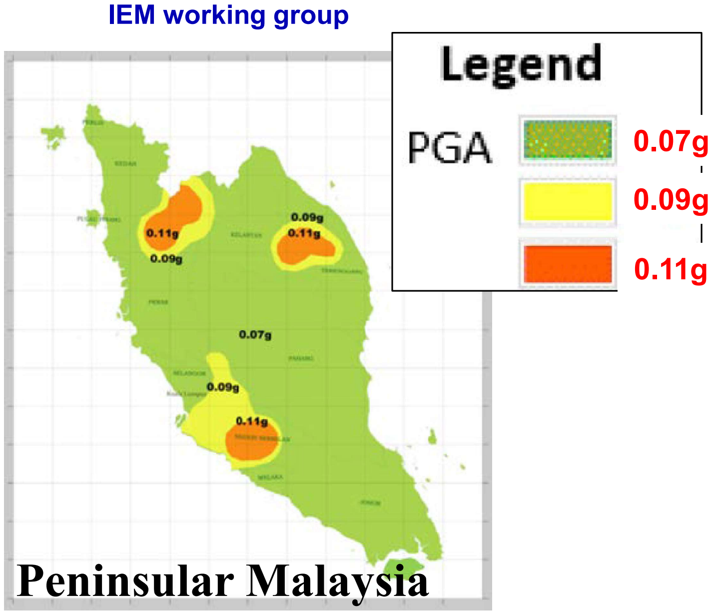
- Unacceptably low *PGA* value of 0.04g for *Kota Kinabalu* (capital city of *Sabah*)
- It is some 50 km from the epicentre of the M6.0 *Ranau* earthquake of 2015

Seismic Design Hazard Maps showing PGA (a_g) values



0.08g at Seremban? (KK is only 0.04g)?

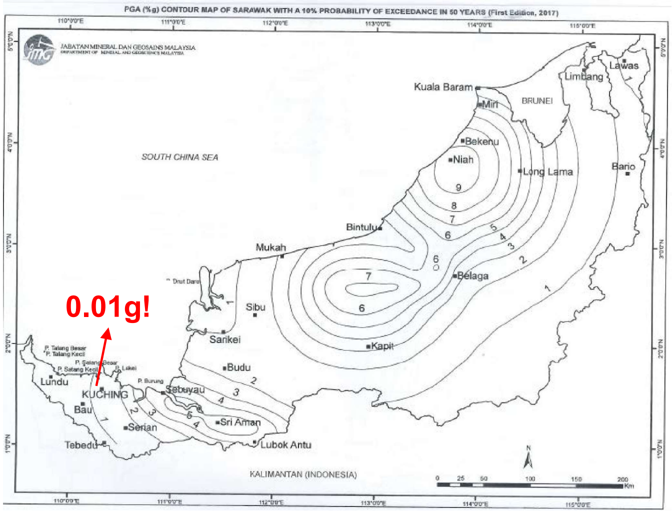
Recommended map prepared by IEM working group

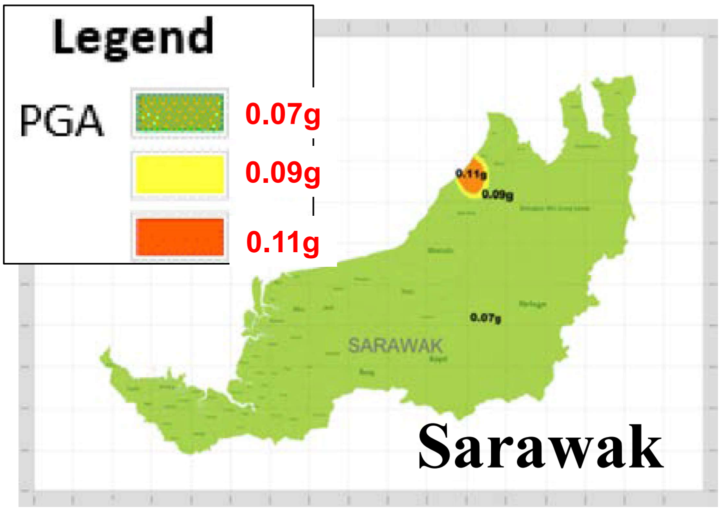


Seismic Design Hazard Maps showing PGA (a_g) values

MALAYSIAN STANDARD MS EN 1998-1:2015 (NATIONAL ANNEX:2017)

Recommended map prepared by IEM working group

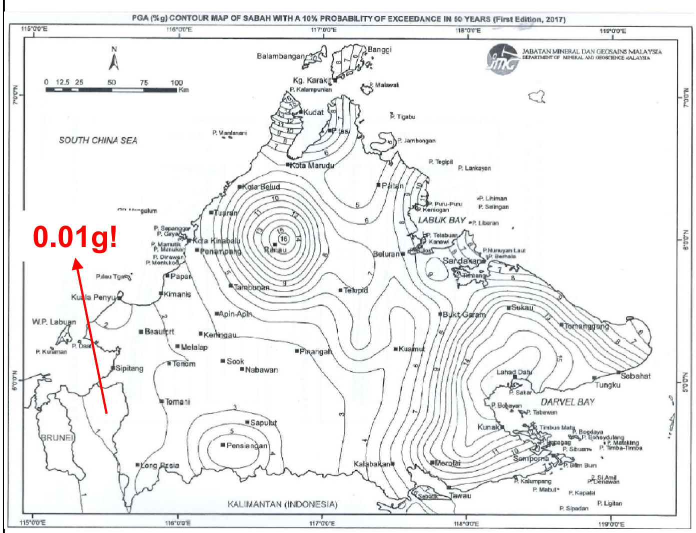


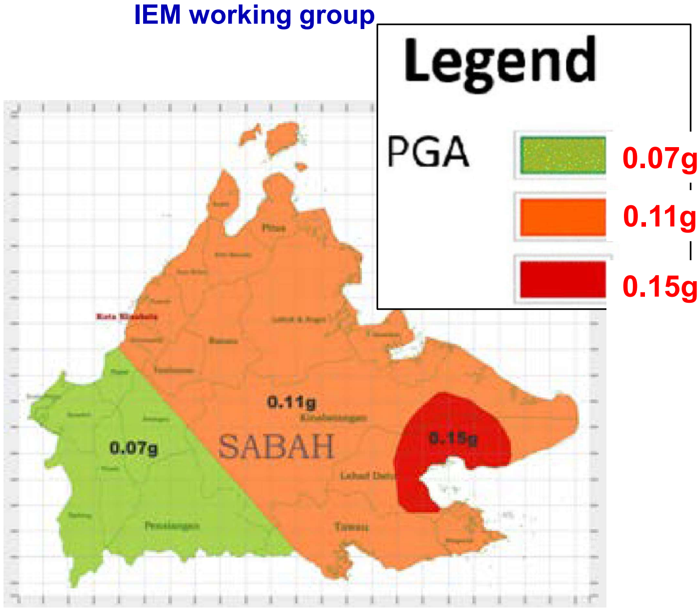


Seismic Design Hazard Maps showing PGA (a_g) values

MALAYSIAN STANDARD MS EN 1998-1:2015 (NATIONAL ANNEX:2017)

Recommended map prepared by IEM working group





Qualification for seismic assessment of PIR

- The seismic action in Malaysia is quiet but not silent, we commonly termed as "low-to-moderate seismicity regions".
- Seismic assessment methods of can be found in EAD 331522 (endorsed draft 2018) in Europe and in AC 308 (2016) in the US.
- Engineers are reminded that it is essential to qualify the PIR system under static loading first as a pre-requisite before proceeding to seismic assessment.

Content

1. Design philosophy of PIR
2. Design provision for Rebar End Anchorage Theory in EN 1992-1-1 (2004)
3. Introduction to design provision for Bonded Anchor Theory in EN 1992-4 (2018)
4. Introduction to strut-and-tie model
5. Notes on seismic actions
6. Conclusion

Conclusion

- The design philosophy of PIR was introduced
  1) REA – Rebar End Anchorage as per EC2-1-1 (2004)
  2) BA – Bonded Anchor as per EC2-4 (2018)
  3) STM – Strut-and-Tie Model
- In REA, splitting failure was elaborated with an α_2' method extended from EC2 for higher bond strength of adhesive.
- In BA, the complex formulation as per EC2-4 (2018) was introduced.
- In STM, definition of strut, tie and nodes were introduced with reference to the authors' ACI paper (2015) and EC2-1-1 (2004)
- Seismic actions in Malaysia was introduced together with PIR seismic assessment.

1-DAY SEMINAR ON

"PERFORMANCE EVALUATION FOR CONCRETE TO CONCRETE CONNECTION: FROM QUALIFICATION TO DESIGN"

End of Presentation on

Session 3: Design Methods:

Rebar End Anchorage Theory, introduction to Bonded Anchor Theory and Strut-and-Tie Design

Dr. Daniel Looi

PhD (HKU) | BEng (Malaya)

Lecturer | Swinburne University of Technology (Sarawak Malaysia)

dlooi@swinburne.edu.my