An engineering analysis of truss-out metal bracket bamboo scaffoldings

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Use of truss-out bamboo scaffoldings

High accident and fatality rate

「狗臂架」鬆脫肇禍　判頭兄長悲痛
搭棚工失足墮樓喪命　15 April 2005 蘋果日報

【本報訊】一對從事搭棚工作兄弟，兄長擔任工程判頭承接工程，弟弟則負責前線工作，昨日三十歲弟弟與工友在旺角西洋菜街一幢大廈七樓外牆搭建竹棚時，失足連人帶用以承托竹枝、俗稱「狗臂架」鐵架飛墮後巷喪命，其兄得悉噩耗傷心不已，勞工處正展開調查。

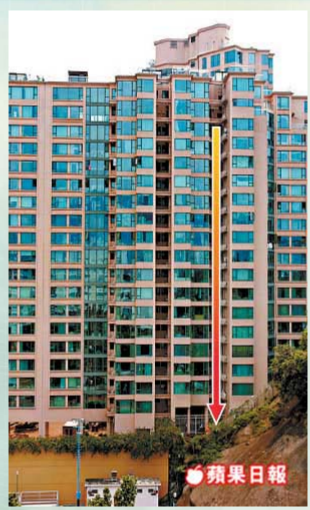
搭棚換窗　兩人跌死　14 July 2005 東方日報

兩名工人在工廠大廈五樓外牆搭建工作台，為廠房更換鋁窗的工程做準備，工作台疑不勝負荷坍塌，兩人無佩戴安全帶下，飛墮地面重傷，送院不治。勞工處職員在現場發現支撐工作台的「狗臂架」只繫上一粒爆炸螺絲

High accident and fatality rate

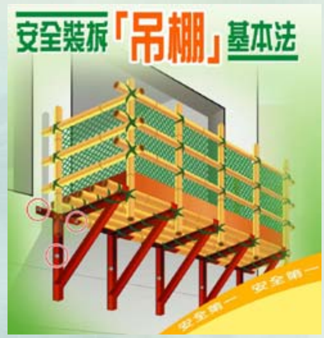
塌狗臂架　勞處調查
一日兩宗奪命工業意外　一粒螺絲累死拆棚工人　19 August 2006 蘋果日報

【本報訊】一顆鬆脫螺絲釀成一宗奪命意外！一名工人昨午在土瓜灣帝庭豪園，拆卸一個位於23樓的外牆竹棚時，懷疑承托竹棚其中一個狗臂架的一粒螺絲鬆脫，導致竹棚無法負荷工人重量倒塌，懸垂半空，工人飛墮地面重傷死亡，勞工處正調查意外原因。



Problems of truss-out bamboo scaffoldings

- Safe?
- Factors affecting their safety?
- Possible improvement?

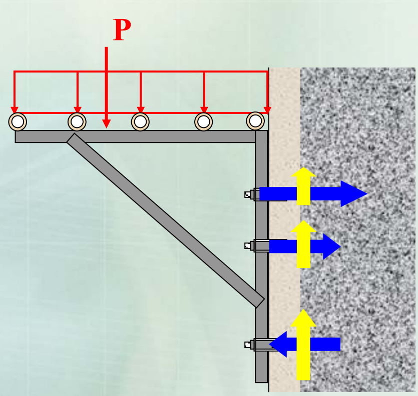


Load-carrying capacity of truss-out bamboo scaffoldings

Scaffolding components

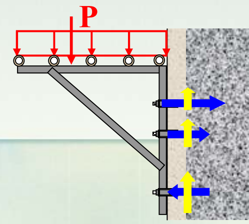
Mechanical behaviour

- Strength of bamboo
- Strength of metal brackets
- Strength of anchor bolts



Strength of bamboo

- Three types of bamboo
  - Kao Jue (BP 篙竹)
  - Mao Jue (PP毛竹)
  - Fir (木杉)



- Strength of bamboo
- Strength of metal brackets
- Strength of anchor bolts

Strength of bamboo

Strength of bamboo

- Mechanical properties for BP under normal compressive test

NL	D (mm)		A (mm^2)		S (MPa)			E (GPa)	
	mean	std	mean	Std	mean	std	95% prob.	mean	std
1/4	53.2	6.8	969.5	365.5	58.6	7.7	45.9	7.9	1.3
1/2	53.4	6.8	969.8	355.4	56.6	6.0	46.7	7.9	1.6
none	54.6	5.5	989.5	295.8	56.0	9.7	40.1	7.6	2.1

Concrete 40 MPa 25 GPa

Steel 500 MPa 200 GPa

Strength of bamboo

- Mechanical properties for BP under 3-point bending test

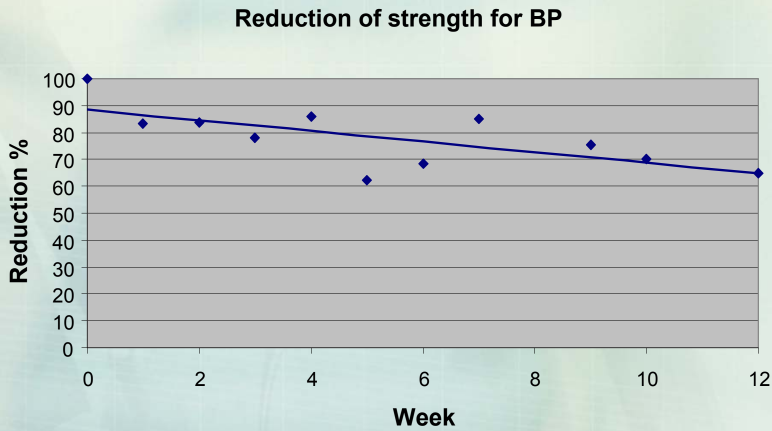
Material	E (GPa)	S (MPa)
Fir	6.3	44.6
PP	11.8	78.7
BP	20.0	80.7

Concrete 25 GPa 40 MPa

Steel 200 GPa 500 MPa

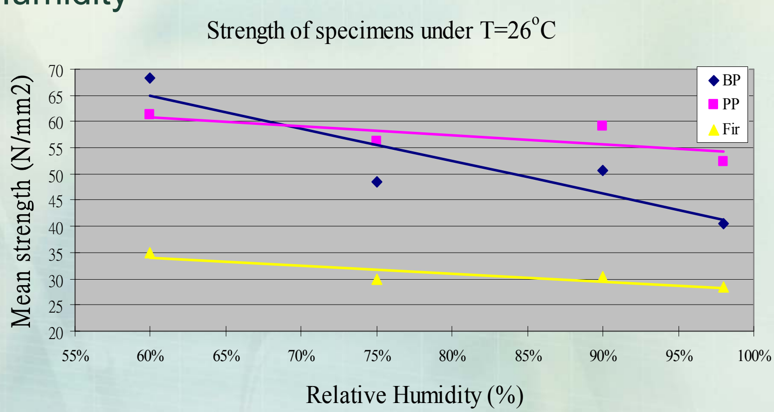
Strength of bamboo

- Aging



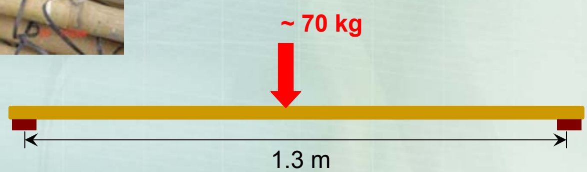
Strength of bamboo

- Humidity

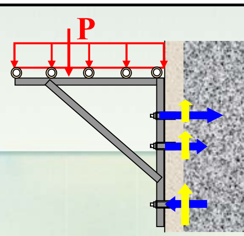


Strength of bamboo

- On the average, can support a concentrated load of 70 kg on a 1.3-m span.

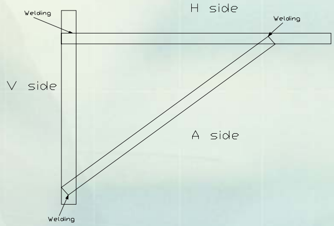


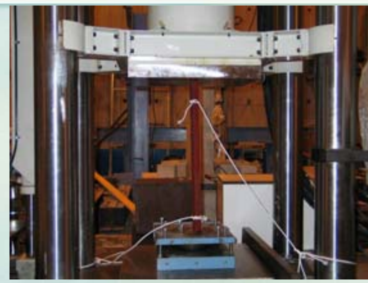
Strength of metal brackets

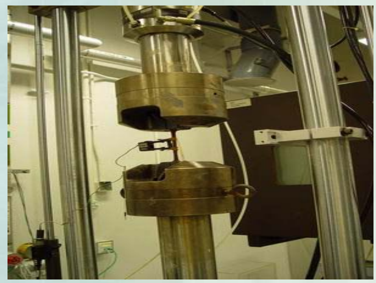


- Strength of bamboo
- Strength of metal brackets
- Strength of anchor bolts

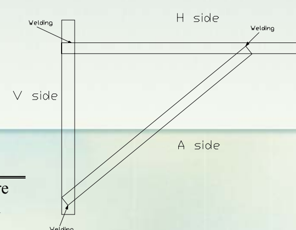
Strength of metal brackets







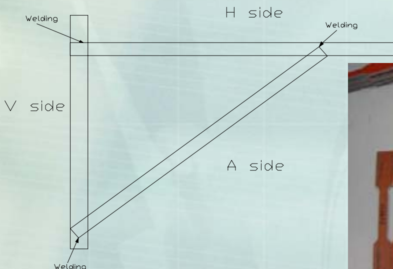
Strength of metal brackets



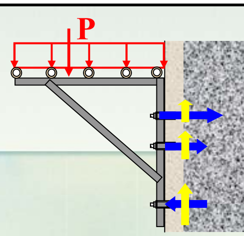
Specimen	Young's Modulus (GPa)	Ultimate Stress (MPa)	Fracture Stress (MPa)	Fracture Strain (%)
		H component		
2-H1	207	380	353	13.8
2-H2	210	395	388	9.0
2-H3	214	397	331	12.7
2-H4	210	384	326	12.7
		C component		
2-C1	183	606	560	26.9
2-C2	186	605	260	15.0
2-C3	187	646	214	14.1
2-C4	182	490	****	****
2-C5	179	483	358	32.0
2-C6	183	617	574	16.9
2-C7	173	488	373	19.0
2-C8	182	489	409	28.7
		V component		
2-V1	214	593	****	****
2-V2	219	574	489	15.7
2-V3	175	593	406	17.5
2-V4	215	553	481	16.3

Strength of metal brackets

- Low-carbon steel
- Fracture strength of 400 – 600 MPa
- Young's modulus of 200 GPa
- Tough, ductile, easily machined



Strength of anchor bolts



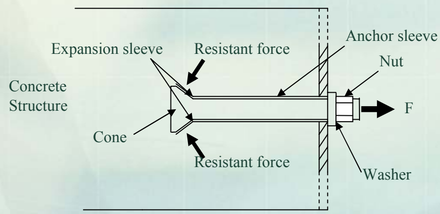
- Attaching metal brackets to wall

•Strength of bamboo
•Strength of metal brackets
•Strength of anchor bolts

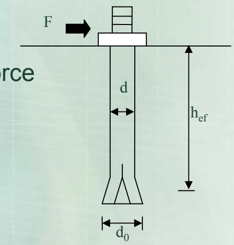
	Embedment depth (mm)	Diameter (mm)
Fook Shing	39.0	12. 8
Bey	46.5	12.5
Hilti	65.0	10.0

Strength of anchor bolts

Pullout force

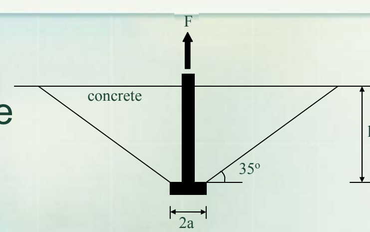


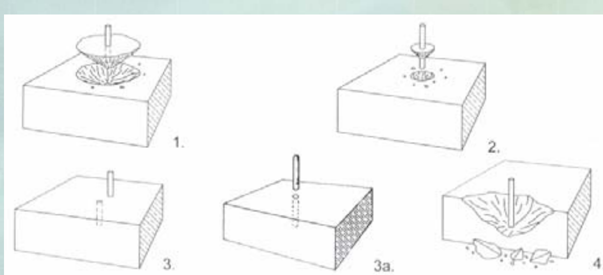
Shear force



Strength of anchor bolts- pullout force

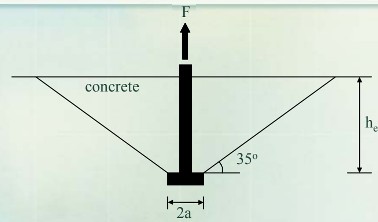
1. Concrete cone failure
2. Combined cone-bond failure
3. Steel failure
4. Edge breaking failure





Strength of anchor bolts- pullout force

- Empirical formulas

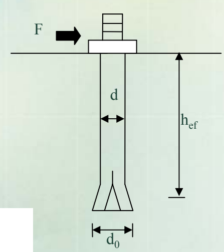


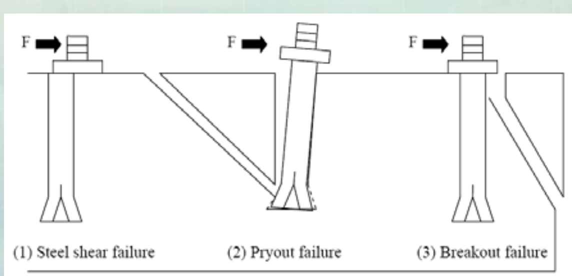
Eligehausen $$F_u = 15.5 f_{cc}^{0.5} h_{ef}^{1.5}$$

ACI $$F_u = 0.96 f_{cc}^{0.5} h_{ef}^{2} \left(1 + \frac{d_h}{h_{ef}}\right)$$

Strength of anchor bolts- shear force

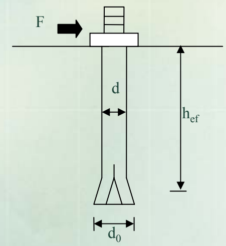
1. Steel shear failure
2. Pryout failure
3. Breakout failure





Strength of anchor bolts- shear force

- Empirical formulas



Steel shear failure (剪力破壞)

$$V_s = 0.6 f_{ut} A_e$$

Pryout failure (撬離破壞)

$$V_{cp} = k_{cp}\psi_{Ng}\psi_{Ne}\psi_{Ncr}(12.5\sqrt{f_c'}h_{ef}^{1.5}) \qquad h_{ef} < 280\text{mm}$$

$$V_{cp} = k_{cp}\psi_{Ng}\psi_{Ne}\psi_{Ncr}(4.75\sqrt{f_c'}h_{ef}^{1.67}) \qquad 280 \le h_{ef} \le 635\text{mm}$$

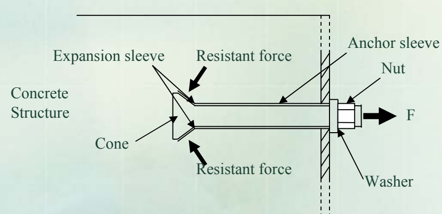
Breakout failure (斷裂破壞)

$$V_{n,c} = \psi_{Vg}\psi_{Ve}\psi_{Vcr}0.84\left(\frac{h_{ef}}{d}\right)^{0.2}\sqrt{d}\sqrt{f_c'}c_1^{1.5}$$

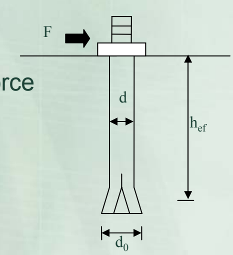
Strength of anchor bolts

- Factors
  - Drilled hole size
  - Anchoring tightness
  - Embedment depth
  - Anchoring location
  - Wall material

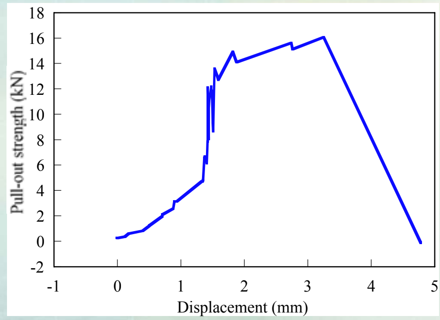
Pullout force



Shear force

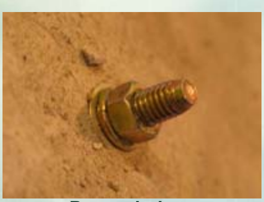


Strength of anchor bolts- Drilled hole size



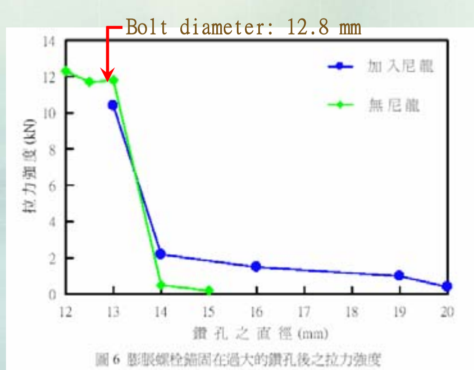
Strength of anchor bolts- Drilled hole size

- Proper drilled hole size is very important !

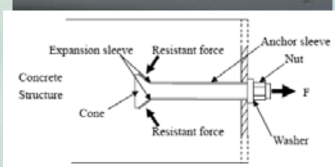


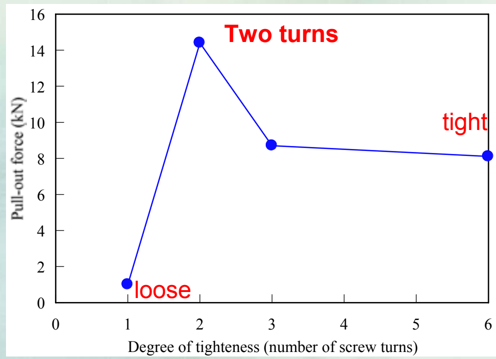
Proper hole

Larger hole with a nylon strip insert

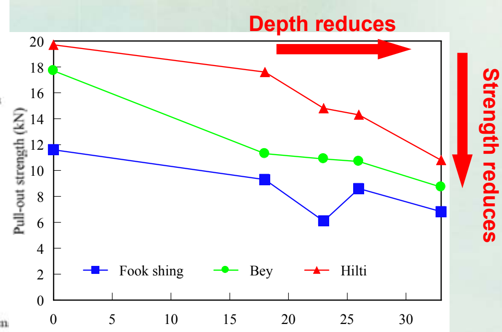


Strength of anchor bolts- Anchoring tightness

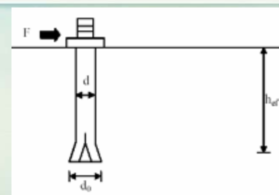


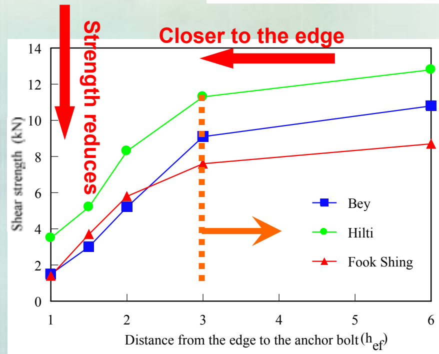


Strength of anchor bolts- Embedment depth



Strength of anchor bolts- Anchoring location





Strength of anchor bolts- Wall material

- Concrete panels

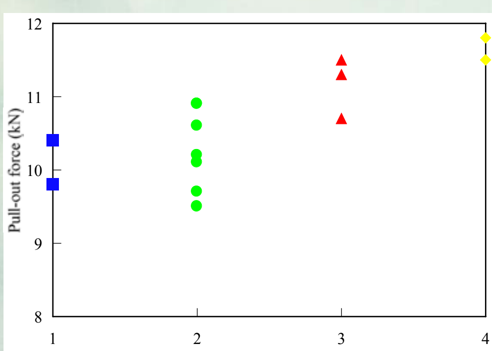
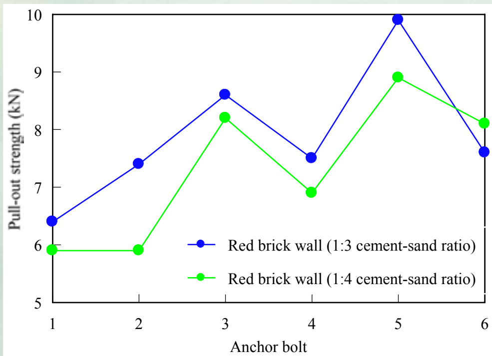


Table 3.6 Results of compressive tests for the concrete panels

Concrete Set	Panel	Specimen	Maximum Load (kN)	Strength (MPa)
I	Panel 1	1	499	22.2
		2	501	22.3
		3	517	23.0
	Panel 2	1	522	23.2
		2	480	21.3
		3	453	20.1
II	Panel 3	1	734	32.7
		2	700	31.1
		3	794	35.3
	Panel 4	1	746	33.2
		2	700	31.1
		3	735	32.7

Strength of anchor bolts- Wall material

- Brick walls



Strength of anchor bolts- Wall material

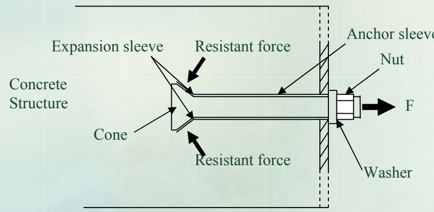
螺栓	混凝土板塊		紅磚牆	
	拉力強度(kN)	位置	拉力強度(kN)	位置
1	8.4	中間	5.3	中間
2			0.8	兩磚之間
3			4.5	中間
4			6.7	中間
平均拉力強度(kN)			4.3	
標準差(kN)			2.5	

Embedded in brick wall
Strength is smaller
Strength variation is larger

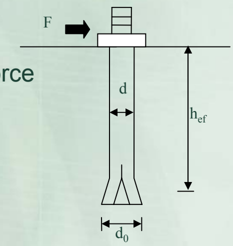
Strength of anchor bolts

- Factors
  - Drilled hole size
  - Anchoring tightness
  - Embedment depth
  - Anchoring location
  - Wall material

Pullout force



Shear force



Load-carrying capacity of scaffoldings- Numerical analysis

Load-carrying capacity

Bolt force = Bolt strength

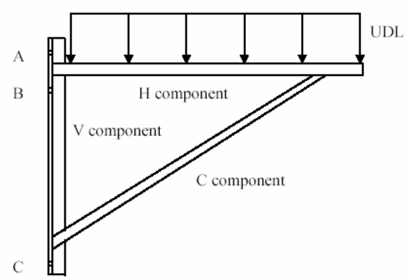


Figure 6.2 A typical metal bracket

Table 6.3 Location of expansion bolts for three cases

Case	Location of Expansion Bolts
1	A
2	A and B
3	A, B and C

Load-carrying capacity of scaffoldings-Numerical analysis

Table 6.1 Pull-out strength of the Fook Shing expansion bolts (in kN)

Base material	Hole	Range	Mean	Std	Mean-3Std	Mean+3Std
Concrete	Fitted	9.5 - 11.8	10.6	0.7	8.5	12.7
	Over-sized	0.4 - 2.2	1.3	0.8	0	3.7
Red-brick wall	Fitted	5.9 - 9.9	7.6	1.2	4.0	11.2
	Over-sized	0.5 - 3.4	1.7	1.3	0	5.6
Sand-brick wall	Fitted	6 - 9.5	7.4	1.9	1.7	13.1
	Over-sized	-	-	-	-	-

Table 6.2 Shear strength of the Fook Shing expansion bolts (in kN)

Base material	Hole	Range	Mean	Std	Mean-3Std	Mean+3Std
Concrete	Fitted	16.0 - 18.9	17.5	1.3	13.6	21.4
	Over-sized	-	-	-	-	-

Load-carrying capacity of scaffoldings-Numerical analysis

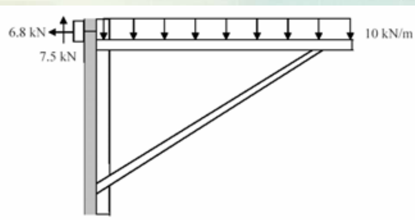


Figure 6.4 Metal bracket anchored at A (Case 1) under UDL of 10 kN/m

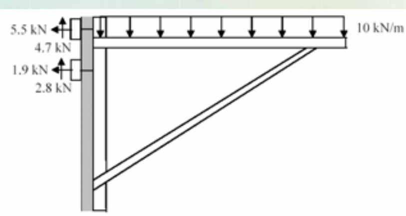


Figure 6.5 Metal bracket anchored at A and B (Case 2) under UDL of 10 kN/m

Load-carrying capacity

Bolt force = Bolt strength

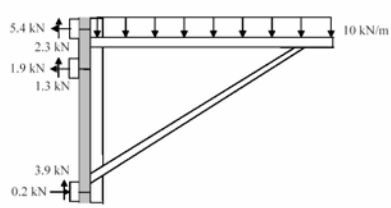


Figure 6.6 Metal bracket anchored at A, B and C (Case 3) under UDL of 10 kN/m

Load-carrying capacity of scaffoldings-Numerical analysis

On concrete panels

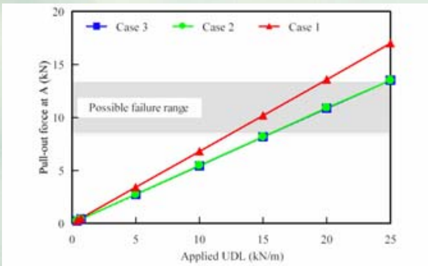


Figure 6.7 Estimated pull-out failure loads for metal brackets mounted on concrete panels

Pullout failure

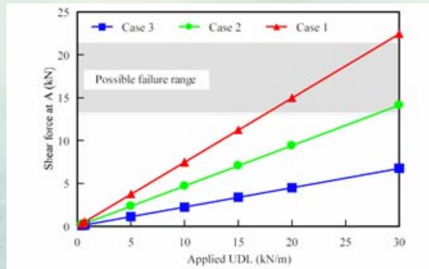


Figure 6.8 Estimated shear failure loads for metal brackets mounted on concrete panels

Shear failure

Load-carrying capacity of scaffoldings-Numerical analysis

On brick walls

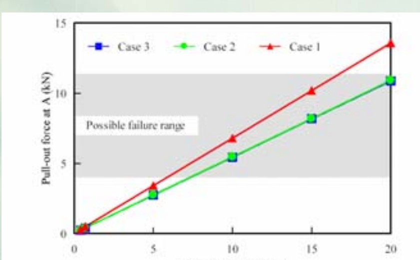


Figure 6.10 Estimated pull-out failure loads for metal brackets mounted on a red-brick wa

Fitted hole

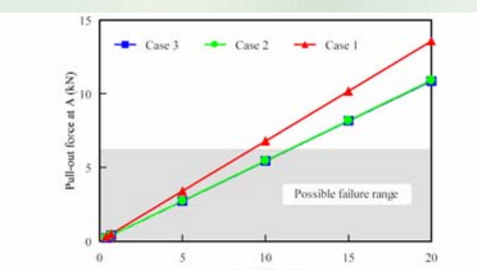


Figure 6.11 Estimated pull-out failure loads for metal brackets embedded in oversized hole on a red-brick wall

Oversized hole

Load-carrying capacity of scaffoldings-
Experimental study

Load-carrying capacity of scaffoldings-
Experimental study

Load-carrying capacity of scaffoldings-Experimental study

Load-carrying capacity of scaffoldings-Experimental study

Anchored on concrete

Failure	Case 1	Case 2	Case 3
Failure UDL (kN/m)	7.1	15.6	20.1
Failure load (kN)	5.2	11.4	14.7

Lower when anchored on brick walls

Anchored on brick

Failure	Case 1	Case 2	Case 3
Failure UDL (kN/m)	5.8	10.1	12.2
Failure load (kN)	4.2	7.4	8.9

Load-carrying capacity of scaffoldings- Experimental study

Anchored in oversized holes (brick wall)

Hole	Failure	Case 1	Case 2	Case 3
Fitted	Failure UDL (kN/m)	5.8	10.1	12.2
	Failure load (kN)	4.2	7.4	8.9
Oversized	Failure UDL (kN/m)	2.6	4.3	4.5
	Failure load (kN)	1.7	2.9	3.0

Fitted

Oversized

Load-carrying capacity of scaffoldings- Experimental study

- Anchored on the edge/side

Anchored on the side

	Panel thickness	
	100 mm	160 mm
Failure UDL (kN/m)	0.4	1.4
Failure load (kN)	0.3	1.0

Anchored on the wall

Failure	Case 1	Case 2	Case 3
Failure UDL (kN/m)	7.1	15.6	20.1
Failure load (kN)	5.2	11.4	14.7

Load-carrying capacity of scaffoldings-Comparison

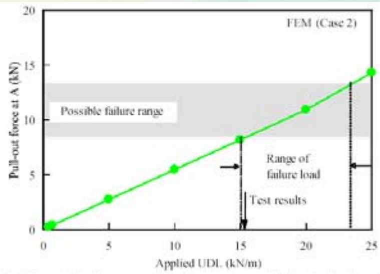


Figure 6.24 Comparison between estimated and measured failure loads for scaffolding mounted on a concrete panel (Case 2: anchored at A and B)

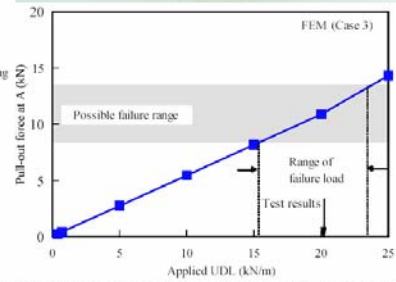


Figure 6.25 Comparison between estimated and measured failure loads for scaffolding mounted on a concrete panel (Case 3: anchored at A, B and C)

Load-carrying capacity of scaffoldings-Comparison

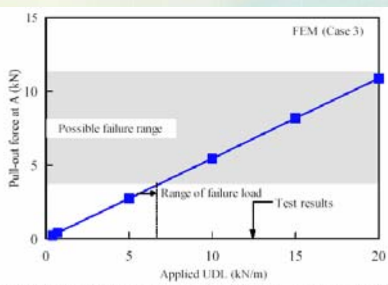


Figure 6.28 Comparison between estimated and measured failure loads for scaffolding mounted on a red-brick wall (Case 3: anchored at A, B and C)

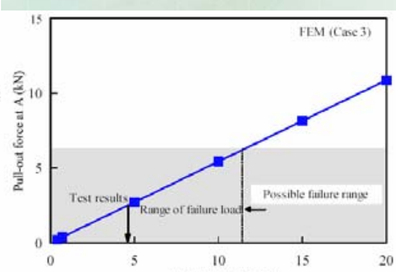


Figure 6.31 Comparison between estimated and measured failure loads for scaffolding mounted in over-sized holes on a red-brick wall (Case 3: anchored at A, B and C)

Load-carrying capacity of scaffoldings-Recommendations

- Do not anchored on brick walls

Load-carrying capacity of scaffoldings-Recommendations

- Anchored in fitted drill holes

Load-carrying capacity of scaffoldings-Recommendations

- Do not anchor on side

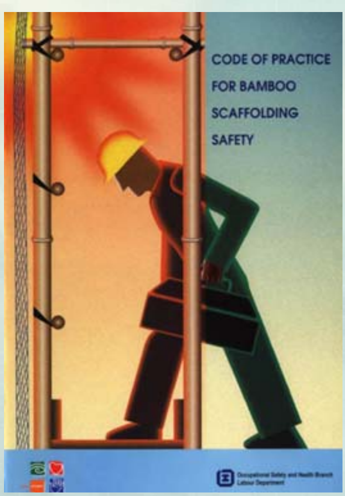
Load-carrying capacity of scaffoldings-Recommendations

- Keep a 3-time distance

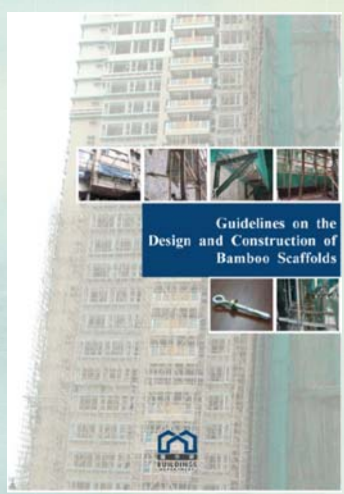
Load-carrying capacity of scaffoldings-Recommendations

- Anchored with proper tightness

Guidelines and Reflections

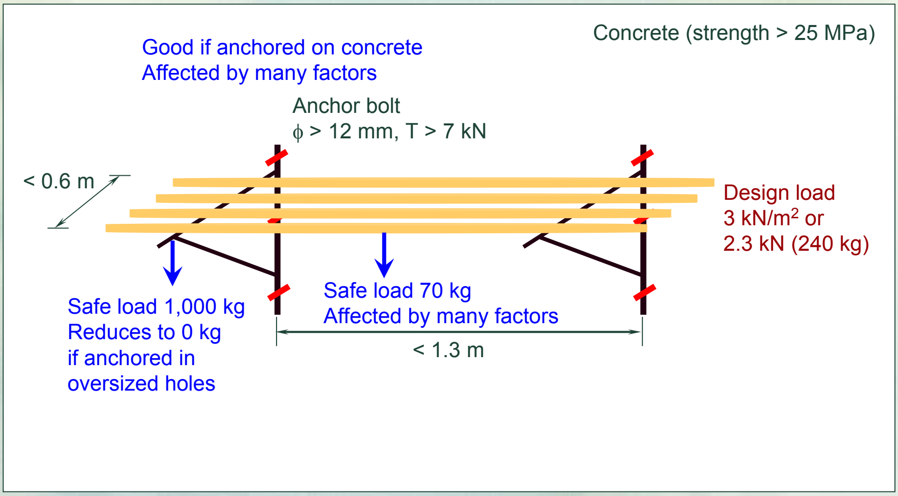


Labour Department



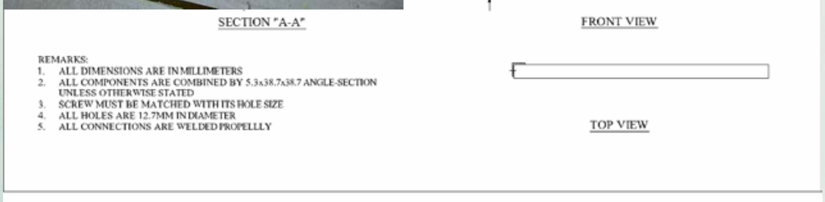
Buildings Department

Guidelines and Reflections

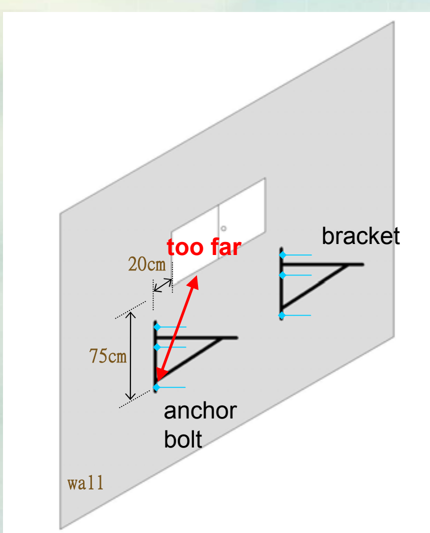


Improvement on metal brackets- T bracket

Problems of current metal brackets



Problems of current metal brackets



Same level of load-carrying capacity
But easier to erect ?

Three types of metal brackets

Type 1: Cross bracket

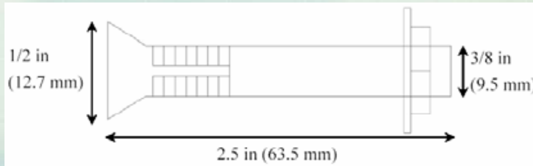
Type 2: I bracket

Type 3: T bracket

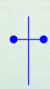
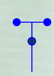
Experimental study

Experimental study

- Fook Shing anchor bolts



Experimental study

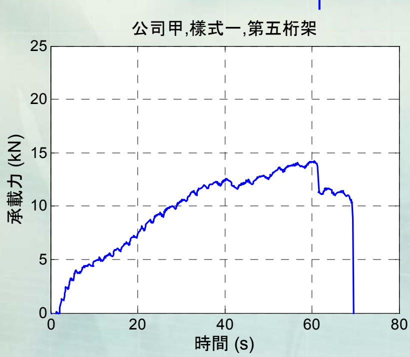
Type	2-bolt anchored	3-bolt anchored
Cross		
I		
T		

Experimental study- Cross bracket

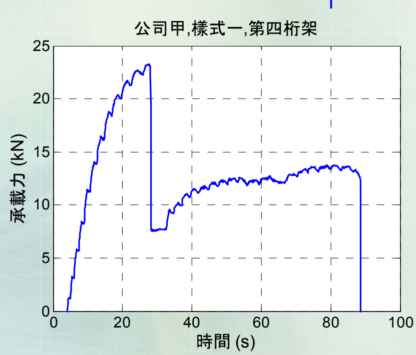
2-bolt anchored | **3-bolt anchored**

Experimental study- Cross bracket

2-bolt anchored



3-bolt anchored



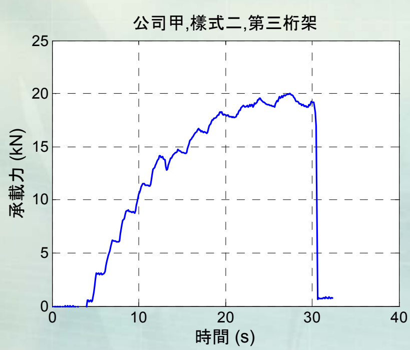
Loading time history

Experimental study- I bracket

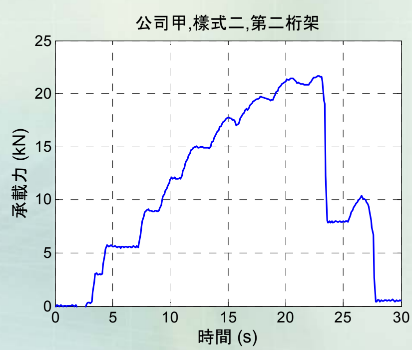
2-bolt anchored | **3-bolt anchored**

Experimental study- I bracket

2-bolt anchored



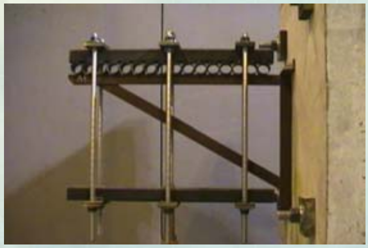
3-bolt anchored

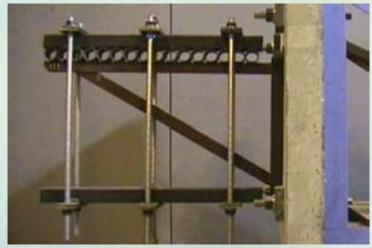


Loading time history

Experimental study- T bracket

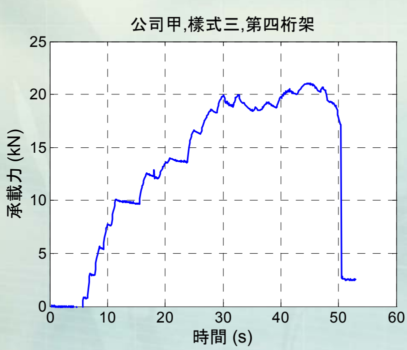
2-bolt anchored | **3-bolt anchored**



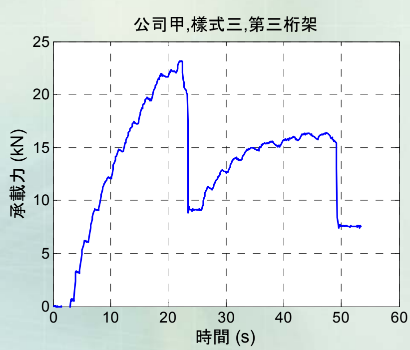


Experimental study- T bracket

2-bolt anchored



3-bolt anchored



Loading time history

Test results

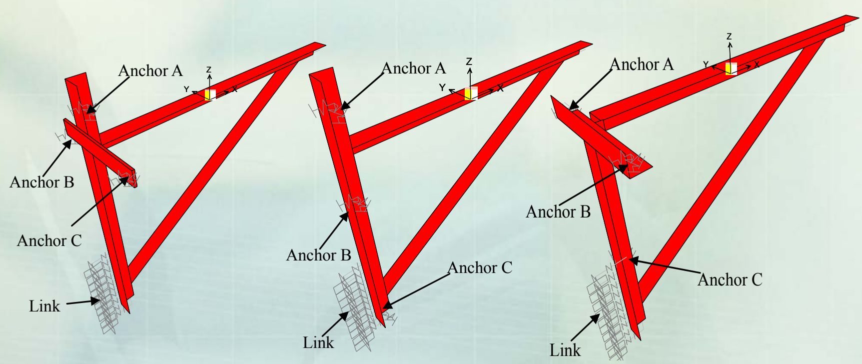
Load-carrying capacity (in kN)

Type	Anchor	Cross bracket	I bracket	T bracket
Company A/ NLC	3-bolt	23	22	23
	2-bolt	14	20	21
Company B/ NLC	3-bolt	25	29	33
	2-bolt	15	30	27
Company C/ NLC	3-bolt	29	31	30
	2-bolt	18	25	25

Smaller

Almost the same

FEM verifications



FEM models

Comparisons

Type	Anchor	Cross bracket		I bracket		T bracket	
		Test	FEM	Test	FEM	Test	FEM
Company A/ NLC	3-bolt	23	22.2	22	20.3	23	24.5
	2-bolt	14	20.8	20	18.2	21	20.6
Company B/ NLC	3-bolt	25	33.1	29	31.5	33	37.8
	2-bolt	15	33.5	30	28.3	27	32.3
Company C/ NLC	3-bolt	29	33.1	31	31.5	30	37.8
	2-bolt	18	33.5	25	28.3	25	32.3

Smaller

Match

Conclusions and recommendations

- The load-carrying capacity of the Cross bracket is the smallest among the three types

Conclusions and recommendations

- Load-carrying capacity

I bracket ~ T bracket

Conclusions and recommendations

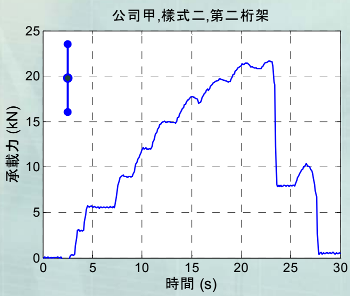
- 3-bolt anchored is always better than 2-bolt anchored

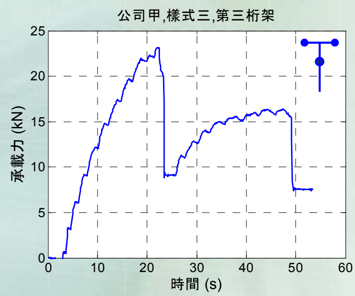
Good (3-bolt)

Type	2-bolt	3-bolt
Cross		
I		
T		

Conclusions and recommendations

- When anchored by 2 bolts, no residual load-carrying capacity is observed
- When anchored by 3 bolts, T bracket exhibits significant residual load-carrying capacity





Conclusions and recommendations

- T bracket
  - Same level of load-carrying capacity as that of I bracket
  - Provides more significant residual capacity if anchored by 3 bolts

Conclusions and recommendations

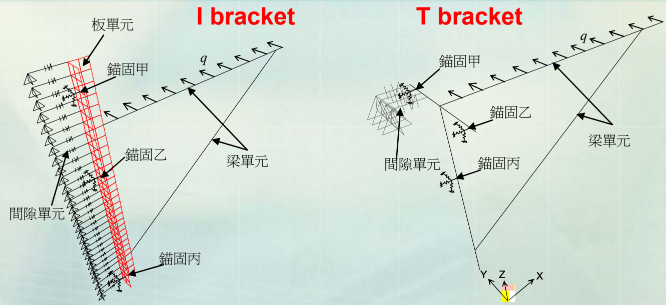
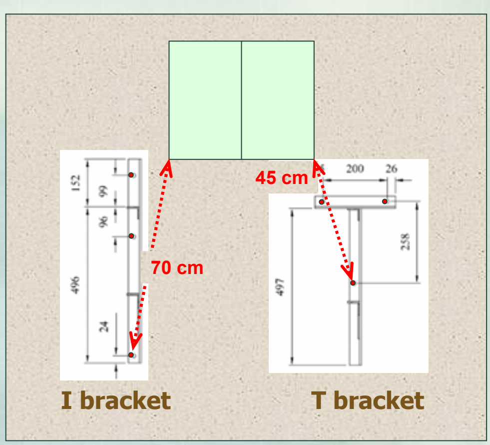


表 戊.1 金屬桁架橫向計算承載力 (以 kN 計)

混凝土板之類型	錨固情況	樣式二 I 形桁架	樣式三 T 形桁架
低 (25 MPa)	三顆螺栓錨固	1.6	6.5
	兩顆螺栓錨固	0.9	6.4
標準 (65 MPa)	三顆螺栓錨固	2.5	10.4
	兩顆螺栓錨固	1.5	10.4

Conclusions and recommendations

- T bracket is easier to erect



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Thank you for your patience…