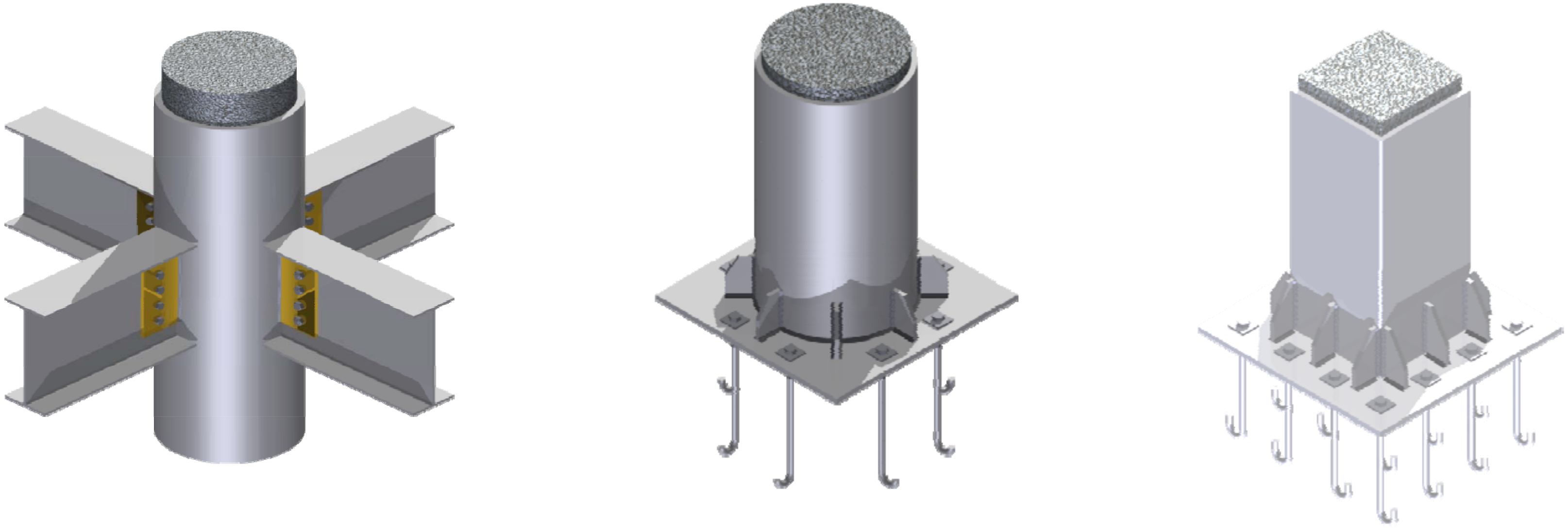
Workshop on Design of Composite Steel-Concrete Structures to EC4 using Excel Spreadsheets
10 April 2015, LT6, Faculty of Engineering, National University of Singapore



Design of Concrete Filled Tubular Members with High Strength Materials

An extension of Eurocode 4 Method to C90/105 Concrete and S550 Steel

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Professor

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Tall buildings using high strength concrete

PETRONAS Tower, Kuala Lumpur, Malaysia
88 storeys, 452m Height
Grade 80 Concrete

International Commence Centre, Hong Kong
118 Storeys, 480m Height
Grade 90 Concrete

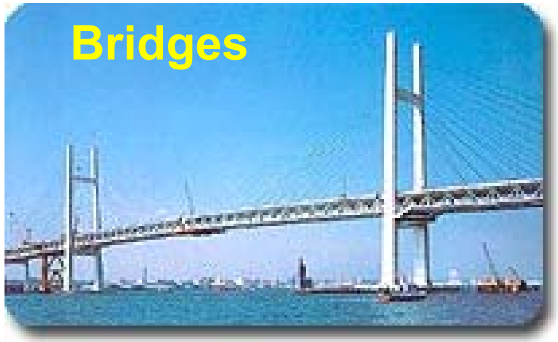
Tall Structures using high strength steel

WFC, Shanghai
Grade 450 steel, 100mm thick

Tokyo Sky Tree™, Japan
Grade 700 steel

Project	Country	Year Completed	Building Height (m)	Concrete (f_{ck}, N/mm^2)	Steel (f_y, N/mm^2)	Used as
225 West Wacker Drive	U.S.A	1988	132	96.5	-	R.C columns
Pacific First Centre	U.S.A	1989	185	131	350	CFST columns
Two-Union building	U.S.A	1989	226	131	350	CFST columns
Two Prudential Plaza	U.S.A	1989	303	82.7	-	R.C columns and walls
Gateway Tower	U.S.A	1990	220	117.2	350	CFST columns
311 South Wacker Drive	U.S.A	1990	293	83	-	R.C columns
Trump Palace	U.S.A	1991	150	82.2	-	R.C columns
Dain Bosworth Tower	U.S.A	1991	164	96.5	-	R.C columns
One Peachtree Centre	U.S.A	1991	257	82.7	-	R.C columns and walls
Society Centre	U.S.A	1991	275	82.7	-	R.C columns and walls
Trump World Tower	U.S.A	2001	262	83		R.C columns
Trump International Hotel & Tower	U.S.A	2009	346	110	-	R.C columns
BurjKhalifa Tower	Saudi Arabia	2010	818	80	-	R.C columns and walls
The federation of the Korean Industries Hall	Korea	2013	245	-	570	Outriggers and belt trusses
Lotte World Tower	Korea	2015	555	-	570	Outriggers, trusses, and CFST columns
W-Comfort Towers	Japan	2004	178	100	-	CFST columns
Obayashi Technical Research Institute	Japan	2010	Multi-storey	160	700	CFST columns
R&D Centre of Sumitomo Metals	Japan	2011	Multi-storey	-	1000	Steel columns
Sky Tree	Japan	2012	634	-	630	Gain tower
Otemachi Tower	Japan	2014	200	150	780	CFST columns
Abeno Harukas	Japan	2014	300	150	590	CFST columns
Taipei 101	Taiwan	2004	508	70	510	CFST columns
Guangzhou West Tower	China	2010	432	90	345	CFST bracings
Goldin 117 Tower	China	2015	597	70	390	CFST columns
Petronas Twin-Towers	Malaysia	1994	452	80	-	R.C columns
International Commerce Centre	Hong Kong	2010	484	90	-	R.C columns and walls
The Sail & Marina Bay	Singapore	2009	245	80	-	R.C columns
The Shard	U.K	2012	306	80	-	R.C columns

Applications of HS Materials



Material strengths allowed in modern design codes

Codes	Steel yield strength (N/mm^2)	Concrete cylinder strength, (N/mm^2)
USA: AISC 360-10	$\leq$ 525	21 ~ 70
China: DBJ/T13-51-2010	235 ~ 430	25 ~ 65
⟶ **Japan: AIJ**	235 ~ 440	18 ~ 90
Europe: EN 1992 (concrete)	-	Up to 90
EN 1993 1-1 & 1-12 (steel)	235 ~ 700	-
EN 1994 (composite)	235 ~ 460	20 ~ 50

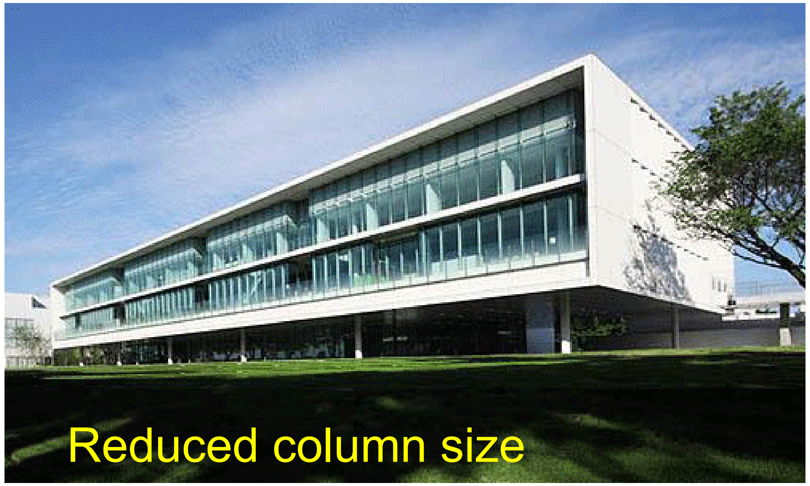
Eurocode 4 (EN 1994) should be extended to cater for higher strength concrete and steel since composite columns exhibit better stiffness and ductility and higher buckling resistance compared with individual steel or reinforced concrete columns.

Composite Construction using ultra high strength materials

Techno Station, Tokyo, Japan
(Completed Sep, 2010)

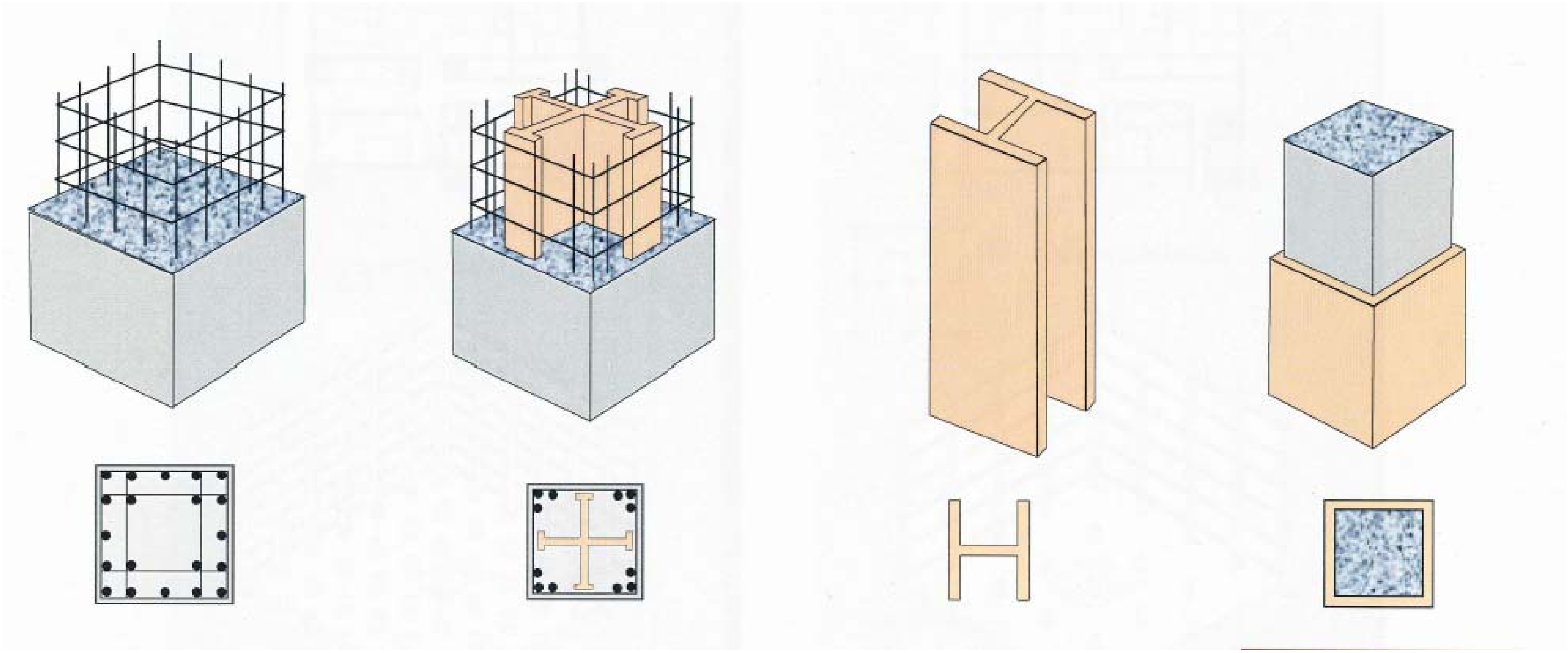
1. Concrete filled steel tubes (steel: 780MPa, concrete: 160MPa) for the main columns; column size reduced from 800mm (based normal strength materials) to 500mm.

2. Ultra high strength fire-reinforced mortar (170MPa) is used for indoor bridges. The depth of the bridge is kept to 335mm.


Reduced column size


Large span workspace

Various Types of Columns



Reinforced Concrete

Up to C90

Concrete Encased

Up to S460/C50

Steel

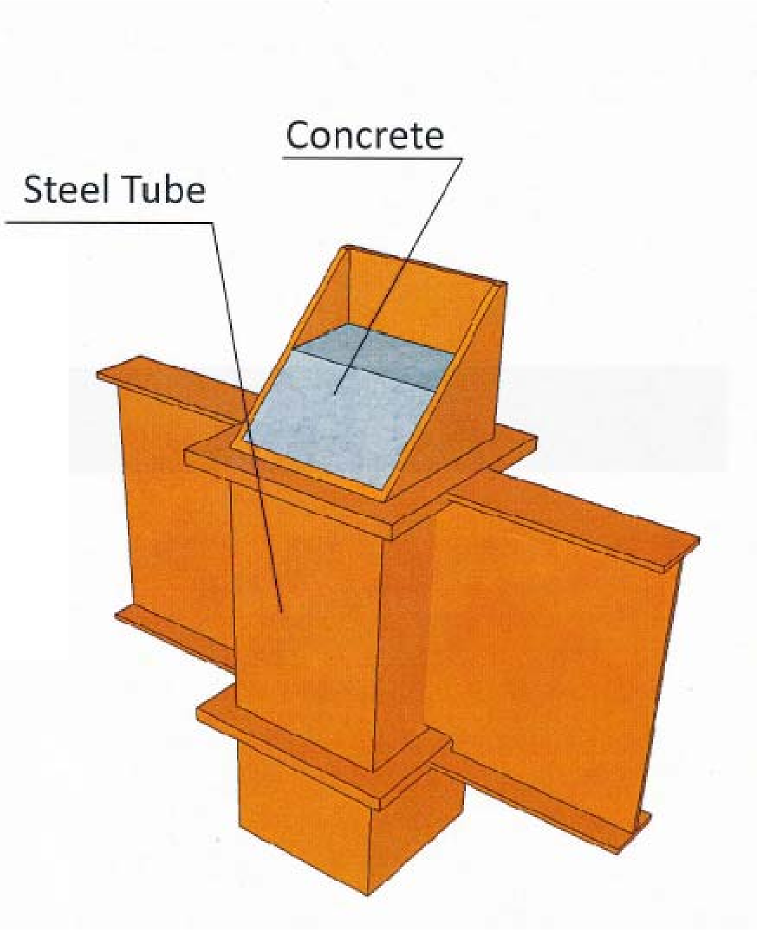
Up to S690

CFT

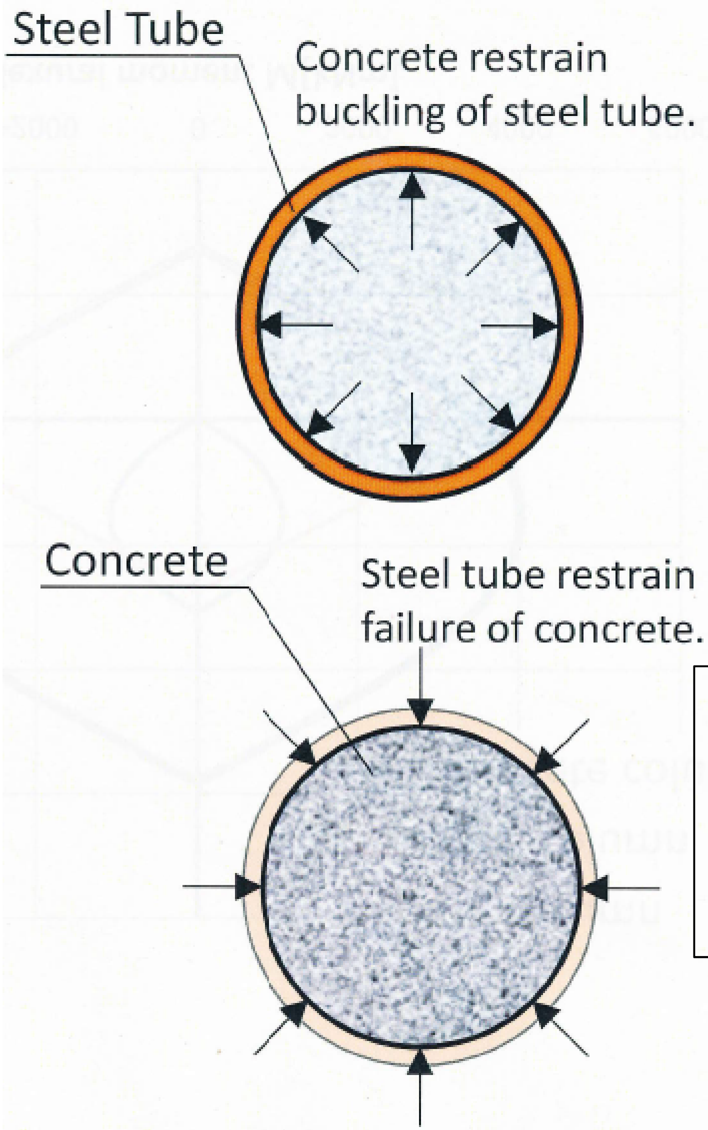
Up to S550/C90

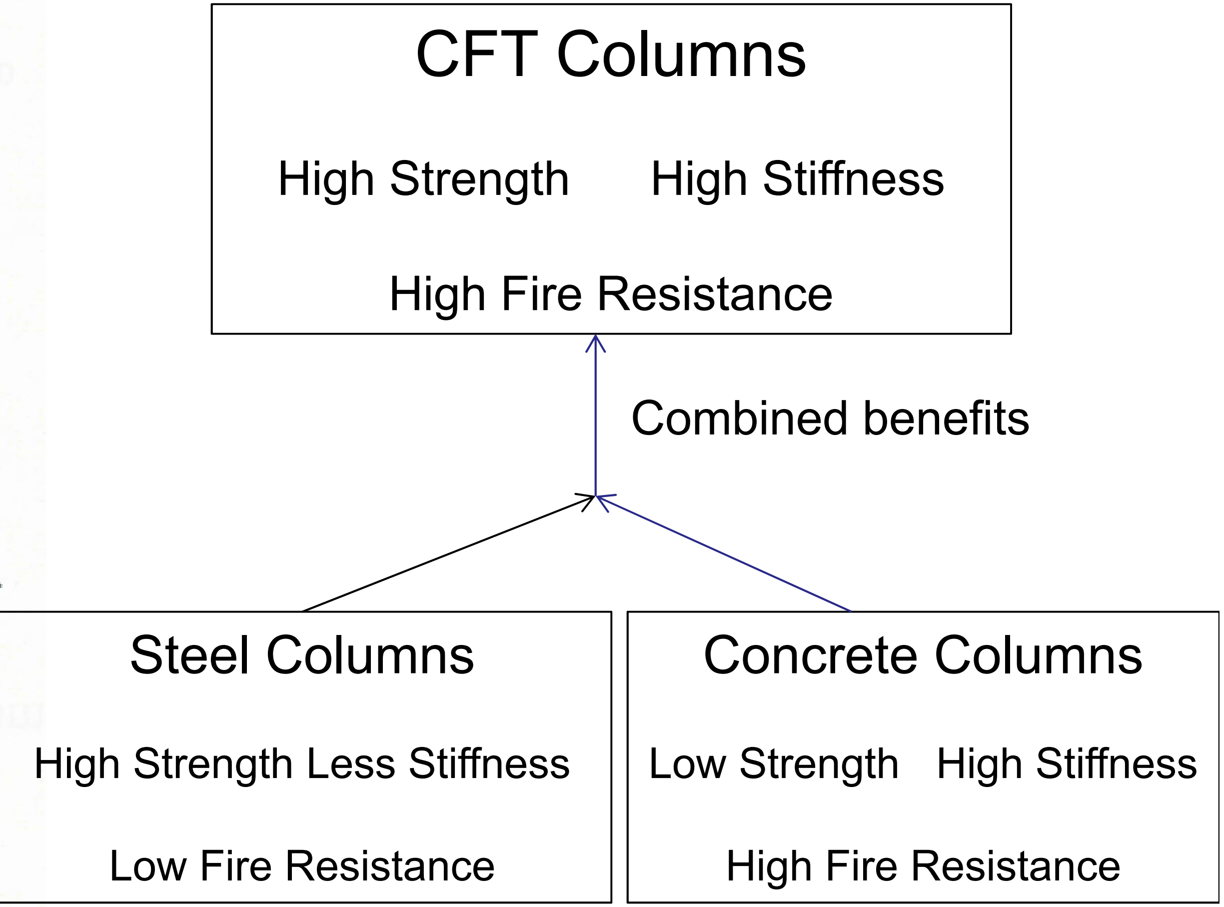
What is Concrete Filled Tube (CFT)?

- Steel tube filled with concrete. Omission of formwork, reducing construction cost and time
- High strength, stiffness and ductility
- Better fire performance than steel columns
- Local buckling of steel tube restrained by concrete
- Smaller cross section dimension



Key Benefits of CFT Columns





CFT Columns

High Strength High Stiffness

High Fire Resistance

Combined benefits

Steel Columns

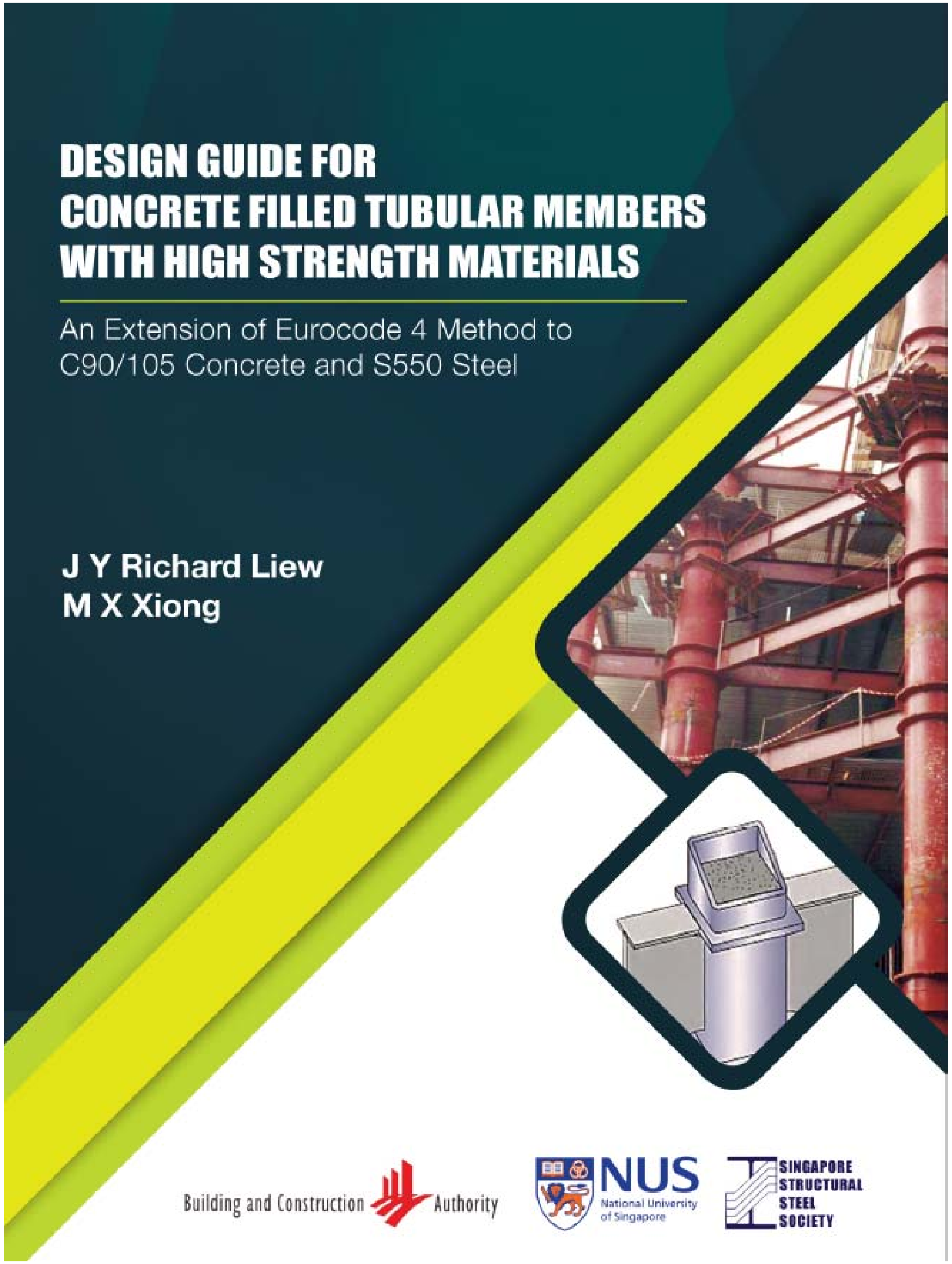
High Strength Less Stiffness

Low Fire Resistance

Concrete Columns

Low Strength High Stiffness

High Fire Resistance



DESIGN GUIDE FOR CONCRETE FILLED TUBULAR MEMBERS WITH HIGH STRENGTH MATERIALS

An Extension of Eurocode 4 Method to
C90/105 Concrete and S550 Steel

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Building and Construction Authority
NUS National University of Singapore
SINGAPORE STRUCTURAL STEEL SOCIETY

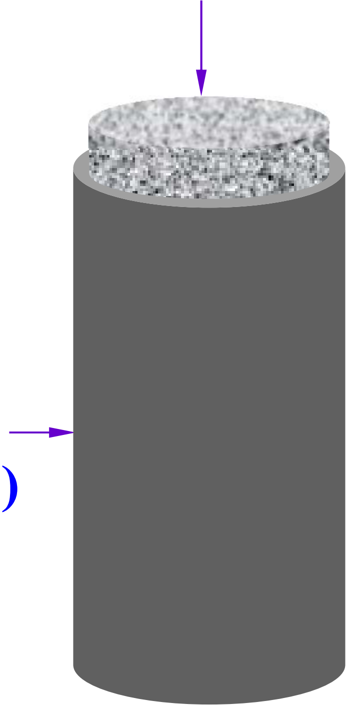
Launching of New Design Guide (2015)

For Singapore

Jointly Published by
NUS, BCA and SSSS

*Design spreadsheet developed

Research supported by A*STAR
Science and Engineering
Research Council Grant

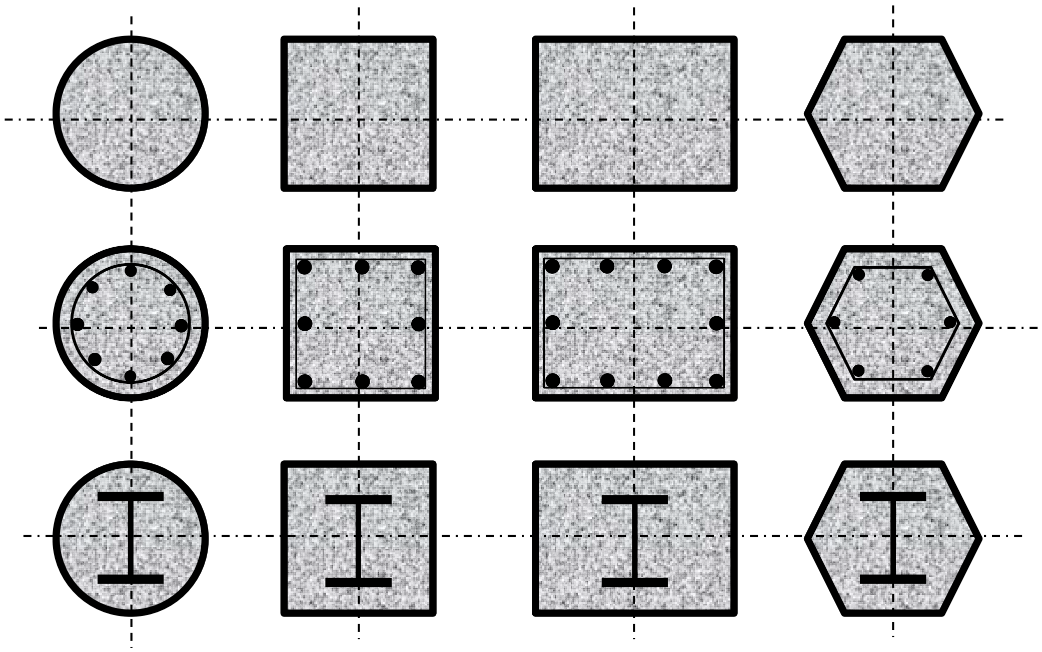


Concrete core
(up to C90)

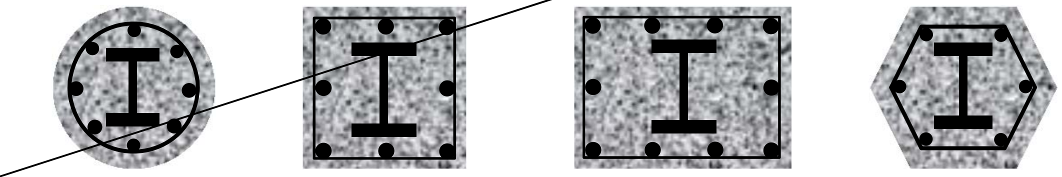
Steel tube
(up to S550)

CFT Column

CFT columns with double symmetric sections



Concrete encased steel section (CES) columns are **not** included in this design guide



Database on CFST column tests

Database by Richard Liew, National University of Singapore

- 2033 test data collected until 2014, extended from Douglas's data base
- Concrete compressive cylinder strength: 8.5N/mm^2 ~ 243N/mm^2;
- Steel yield strength: 178N/mm^2 ~ 853N/mm^2;
- Member height to section smaller dimension ratio: 0.67 ~ 60;
- Relative column slenderness ratio $\bar{\lambda}$: 0.02 ~ 1.30.
- Concrete encased sections are excluded;
- Stainless steel and aluminium sections are excluded;
- Section size less than or equal to 100mm are excluded.
- Members involving preload effect, sustained loading for creep and shrinkage, and dynamic loadings are excluded;
- Class 4 slender steel sections, as stipulated in EN 1994-1-1, are excluded;

Influence of concrete strength

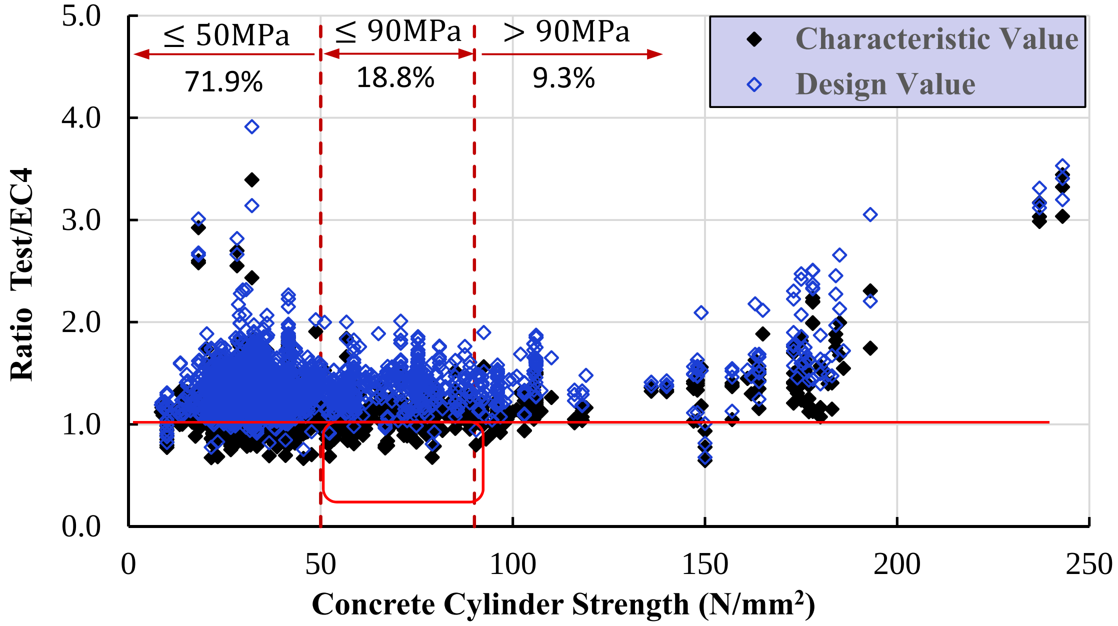
Type of column		Compressive cylinder strength of concrete		
		≤50 N/mm^2	51 to 90 N/mm^2	>90 N/mm^2
All test data	Nos.	1461	382	190
	Test/EC4 ≥ 1	77.3% (98.3%)	67.0% {97.6%}	62.6% {98.4%}
	Av.	1.133 (1.339)	1.052 {1.361}	1.034 {1.597}
	St. Dev.	0.210 (0.240)	0.132 {0.186}	0.132 {0.463}

value1 = based on characteristic strengths of steel and concrete;

(value2) = design strengths;

[value3] = characteristic strengths with reduction factor η for concrete;

{value4} = design strengths with reduction factor η for concrete.



Influence of concrete strength

Type of column		Compressive cylinder strength of concrete		
		≤50 N/mm^2	51 to 90 N/mm^2	>90 N/mm^2
Axially loaded circular cross section	Nos.	295	130	**44**
	Test/EC4 ≥ 1	66.8%	59.2%	**47.7%**
	Av.	1.068	1.023	**1.016**
	St. Dev.	0.136	0.111	**0.104**
Axially loaded circular column	Nos.	383	60	**22**
	Test/EC4 ≥ 1	85.9%	68.3%	**81.8%**
	Av.	1.186	1.039	**1.085**
	St. Dev.	0.24	0.110	**0.095**
Circular beam-column	Nos.	240	66	**46**
	Test/EC4 ≥ 1	82.1%	71.2%	**69.6%**
	Av.	1.192	1.086	**1.008**
	St. Dev.	0.217	0.182	**0.172**
Axially loaded rectangular cross section	Nos.	282	63	**39**
	Test/EC4 ≥ 1	80.1%	68.3%	**56.4%**
	Av.	1.122	1.068	**1.032**
	St. Dev.	0.150	0.123	**0.093**
Axially loaded rectangular column	Nos.	101	40	**12**
	Test/EC4 ≥ 1	62.4%	70.0%	**58.3%**
	Av.	1.059	1.057	**1.095**
	St. Dev.	0.140	0.134	**0.206**
Rectangular beam-column	Nos.	160	23	**27**
	Test/EC4 ≥ 1	73.1%	87.0%	**70.4%**
	Av.	1.107	1.099	**1.044**
	St. Dev.	0.279	0.112	**0.115**

Values are based on the characteristic strengths of steel and concrete.

Extension of EC4 using high strength concrete

For high strength concrete with $f_{ck} > 50\mathrm{N/mm^2}$, the cylinder strength is reduced by :

$$\eta = 1.0 - (f_{ck} - 50)/200$$

Strength classes	C55/67	C60/75	C70/85	C80/95	C90/105
Effective compressive strength (N/mm²)	54	57	63	68	72
% Reduction	2.5%	5.0%	10.0%	15.0%	20.0%

For high strength concrete with $f_{ck} > 50\mathrm{N/mm^2}$, the secant modulus is determined by:

$$E_{cm} = 22[(\eta.f_{ck} + 8)/10]^{0.3}$$

Strength classes	C55/67	C60/75	C70/85	C80/95	C90/105
Modified secant modulus (GPa)	38.0	38.6	39.6	40.4	41.1
% Reduction	0.7%	1.3%	2.8%	4.3%	5.9%

Design of CFSTs
High Strength Concrete with Reduction Factor

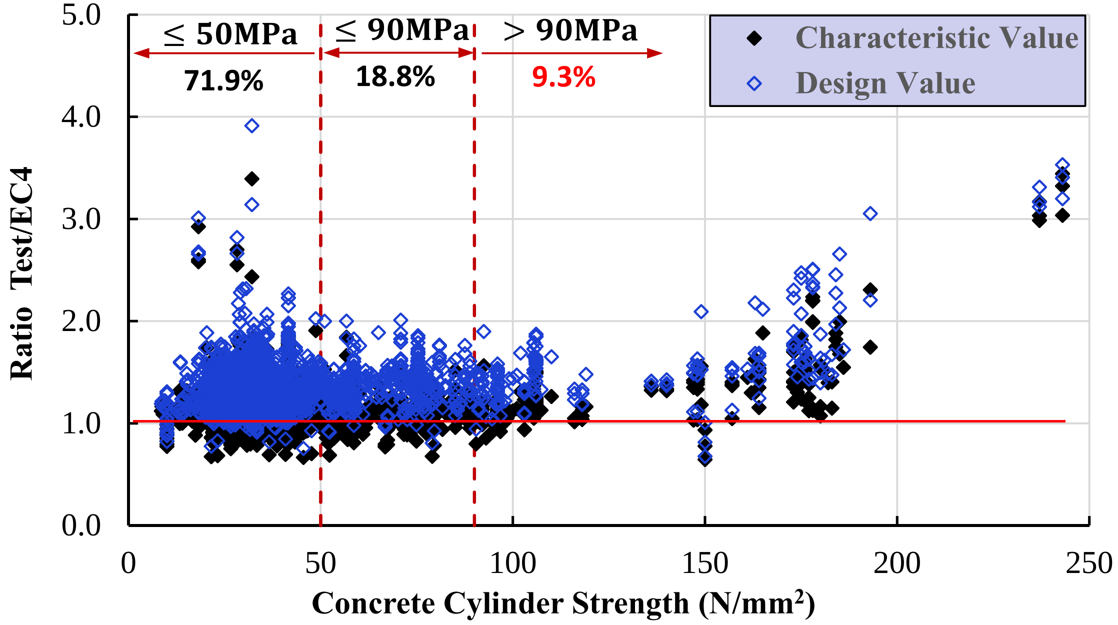
Type of column		Compressive cylinder strength of concrete		
		≤50 N/mm²	51 to 90 N/mm²	>90 N/mm²
All test data	Nos.	1461	382	190
	Test/EC4 ≥ 1	77.3% (98.3%)	[78.3%] {97.6%}	[93.2%] {98.4%}
	Av.	1.133 (1.339)	[1.094] {1.361}	[1.345] {1.597}
	St. Dev.	0.210 (0.240)	[0.141] {0.186}	[0.428] {0.463}

value1 based on characteristic strengths of steel and concrete;

(value2) based on design strengths;

[value3] based on characteristic strengths with reduction factor η for concrete;

{value4} based on design strengths with reduction factor η for concrete.



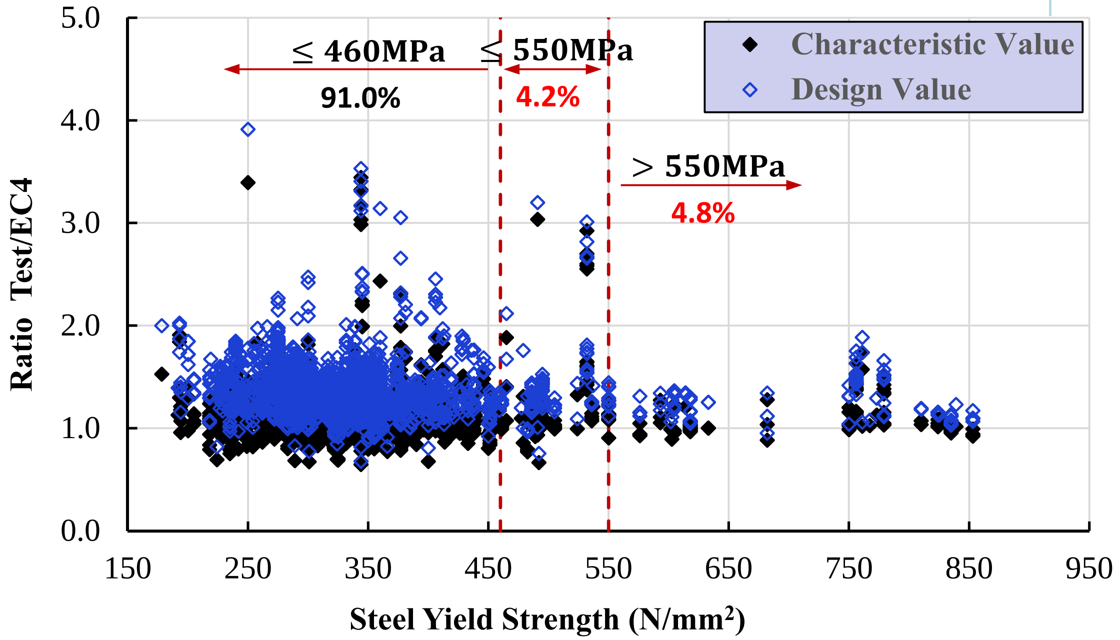
Design of CFST
High Strength Concrete with Reduction Factor

Type of column		**Compressive cylinder strength of concrete**		
		≤50 N/mm²	**51 to 90 N/mm²**	**>90 N/mm²**
Axially loaded circular cross section	Nos.	295	130	44
	Test/EC4 ≥ 1	66.8% (99.3%)	[66.9%] {97.7%}	[100%] {100%}
	Av.	1.068 (1.354)	[1.062] {1.383}	[1.415] {1.838}
	St. Dev.	0.136 (0.168)	[0.132] {0.190}	[0.291] {0.391}
Axially loaded circular column	Nos.	383	60	22
	Test/EC4 ≥ 1	85.9% (97.4%)	[83.3%] {98.3%}	[100%] {100%}
	Av.	1.186 (1.388)	[1.075] {1.339}	[1.319] {1.633}
	St. Dev.	0.246 (0.267)	[0.121] {0.162}	[0.254] {0.321}
Circular beam-column	Nos.	240	66	46
	Test/EC4 ≥ 1	82.1% (98.8%)	[81.8%] {98.5%}	[80.4%] {93.5%}
	Av.	1.192 (1.352)	[1.136] {1.356}	[1.523] {1.674}
	St. Dev.	0.217 (0.237)	[0.189] {0.216}	[0.728] {0.719}
Axially loaded rectangular cross section	Nos.	282	63	39
	Test/EC4 ≥ 1	80.1% (99.6%)	[90.5%] {96.8%}	[100%] {100%}
	Av.	1.122 (1.287)	[1.118] {1.330}	[1.239] {1.409}
	St. Dev.	0.150 (0.196)	[0.117] {0.168}	[0.159] {0.166}
Axially loaded rectangular column	Nos.	101	40	12
	Test/EC4 ≥ 1	62.4% (94.1%)	[77.5%] {95.0%}	[100%] {100%}
	Av.	1.059 (1.220)	[1.099] {1.321}	[1.246] {1.485}
	St. Dev.	0.140 (0.172)	[0.140] {0.177}	[0.242] {0.261}
Rectangular beam-column	Nos.	160	23	27
	Test/EC4 ≥ 1	73.1% (98.1%)	[87.0%] {100%}	[85.2%] {100%}
	Av.	1.107 (1.338)	[1.128] {1.461}	[1.147] {1.364}
	St. Dev.	0.279 (0.341)	[0.102] {0.148}	[0.177] {0.177}

value1 is based on the characteristic strengths of steel and concrete; (value2) is based on design strengths; [value3] is based on characteristic strengths with reduction factor η for concrete; {value4} is based on design strengths with reduction factor η for concrete

Influence of steel strength of Test/EC4 Ratio

Types of column		Yield strength of steel		
		≤460N/mm²	≤550N/mm²	>550N/mm²
All test data	Nos.	1850	86	97
	Test/EC4 ≥ 1	79.0% (98.3%)	84.9% (95.3%)	73.2% (99.0%)
	Av.	1.142 (1.370)	1.256 (1.435)	1.114 (1.244)
	St. Dev.	0.225 (0.262)	0.455 (0.440)	0.179 (0.197)



Influence of steel strength

Types of column		Yield strength of steel		
		≤460N/mm^2	≤550N/mm^2	>550N/mm^2
Axially loaded circular cross section	Nos.	450	5	14
	Test/EC4 ≥ 1	71.6% (99.6%)	**40.0% (40.0%)**	28.6% (100%)
	Av.	1.105 (1.418)	**0.922 (1.133)**	0.964 (1.173)
	St. Dev.	0.186 (0.246)	**0.200 (0.215)**	0.043 (0.073)
Axially loaded circular column	Nos.	414	38	13
	Test/EC4 ≥ 1	85.7% (97.6%)	89.5% (100%)	92.3% (92.3%)
	Av.	1.158 (1.385)	1.399 (1.532)	1.160 (1.270)
	St. Dev.	0.179 (0.225)	0.544 (0.526)	0.112 (0.122)
Circular beam-column	Nos.	346	6	Need research
	Test/EC4 ≥ 1	82.7% (98.0%)	33.3% (100%)	
	Av.	1.223 (1.391)	1.351 (1.639)	
	St. Dev.	0.335 (0.341)	0.839 (0.802)	
Axially loaded rectangular cross section	Nos.	308	21	55
	Test/EC4 ≥ 1	84.7% (99.0%)	100% (100%)	72.7% (100%)
	Av.	1.140 (1.328)	1.132 (1.310)	1.093 (1.183)
	St. Dev.	0.152 (0.193)	0.070 (0.096)	0.154 (0.173)
Axially loaded rectangular column	Nos.	145	8	Need Research
	Test/EC4 ≥ 1	68.3% (95.2%)	87.5% (87.5%)	
	Av.	1.079 (1.263)	1.182 (1.347)	
	St. Dev.	0.142 (0.182)	0.335 (0.375)	
Rectangular beam-column	Nos.	187	8	15
	Test/EC4 ≥ 1	73.8% (98.4%)	87.5% (100%)	100% (100%)
	Av.	1.100 (1.339)	1.110 (1.430)	1.287 (1.514)
	St. Dev.	0.255 (0.319)	0.138 (0.153)	0.242 (0.189)

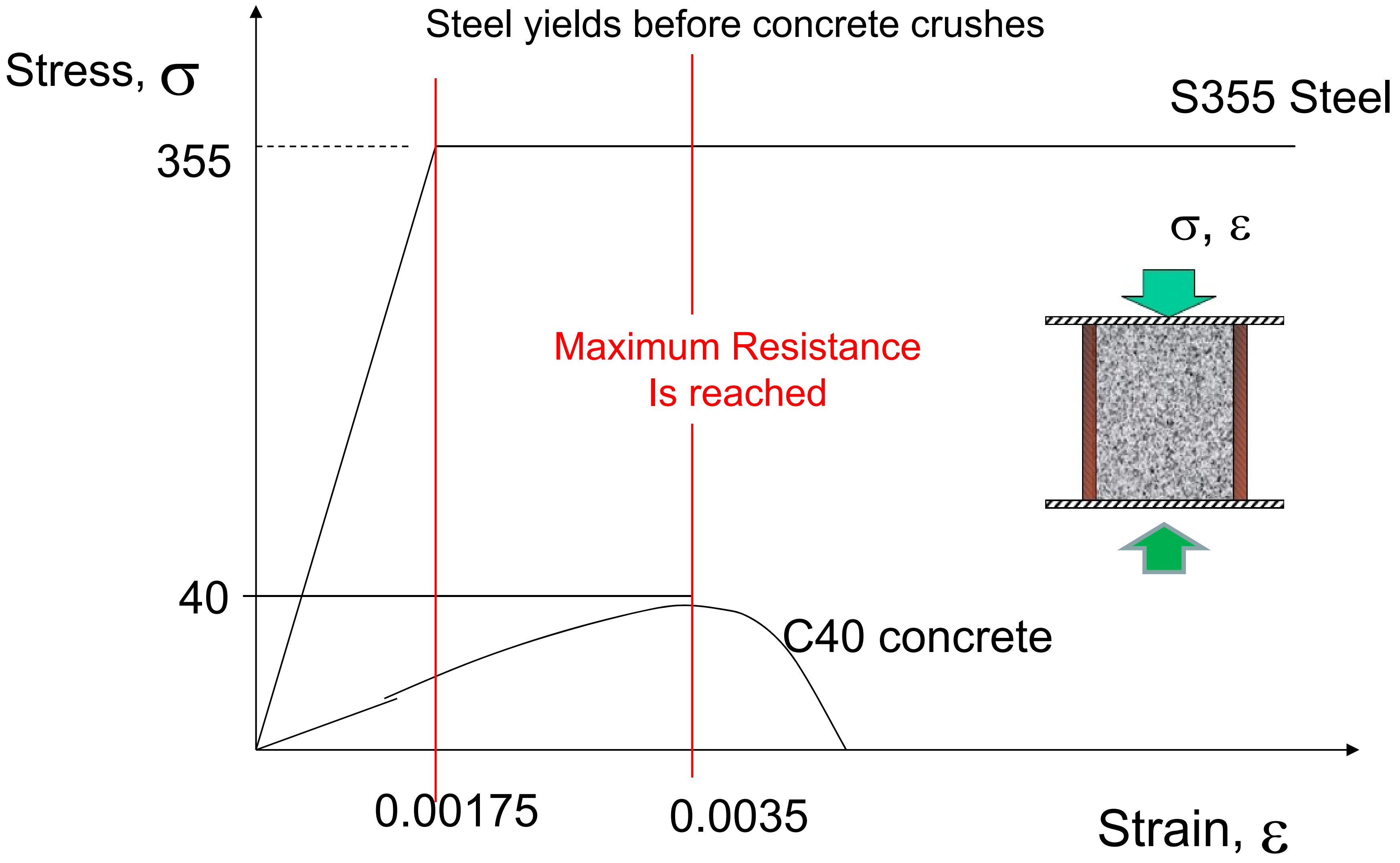
For the value1, (value2) in the table, value1 is based on characteristic strengths of steel and concrete; (value2) is based on design strengths. For concrete with f_{ck}>50N/mm^2, the reduction factor η is considered for the concrete compressive strength and the secant modulus of concrete is modified accordingly.

Material Compatibility between Steel grade and Concrete Class

	S235	S275	S355	S420	S460	S500	S550	S620	S690
C12/15	√	√	√	×	×	×	×	×	×
C16/20	√	√	√	×	×	×	×	×	×
C20/25	√	√	√	×	×	×	×	×	×
C25/30	√	√	√	√	×	×	×	×	×
C30/37	√	√	√	√	×	×	×	×	×
C35/45	√	√	√	√	√	×	×	×	×
C40/50	√	√	√	√	√	×	×	×	×
C45/55	√	√	√	√	√	√	×	×	×
C50/60	√	√	√	√	√	√	×	×	×
C55/67	√	√	√	√	√	√	×	×	×
C60/75	√	√	√	√	√	√	×	×	×
C70/85	√	√	√	√	√	√	√	×	×
C80/95	√	√	√	√	√	√	√	×	×
C90/105	√	√	√	√	√	√	√	×	×

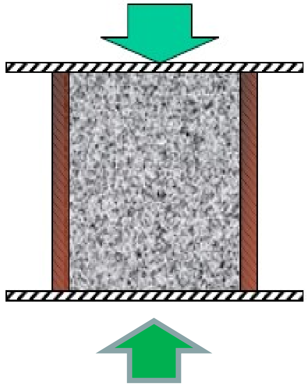
Notes: "√" indicates compatible materials and "×" is not recommended.

Compatibility of Materials for Concrete Filled Tubes

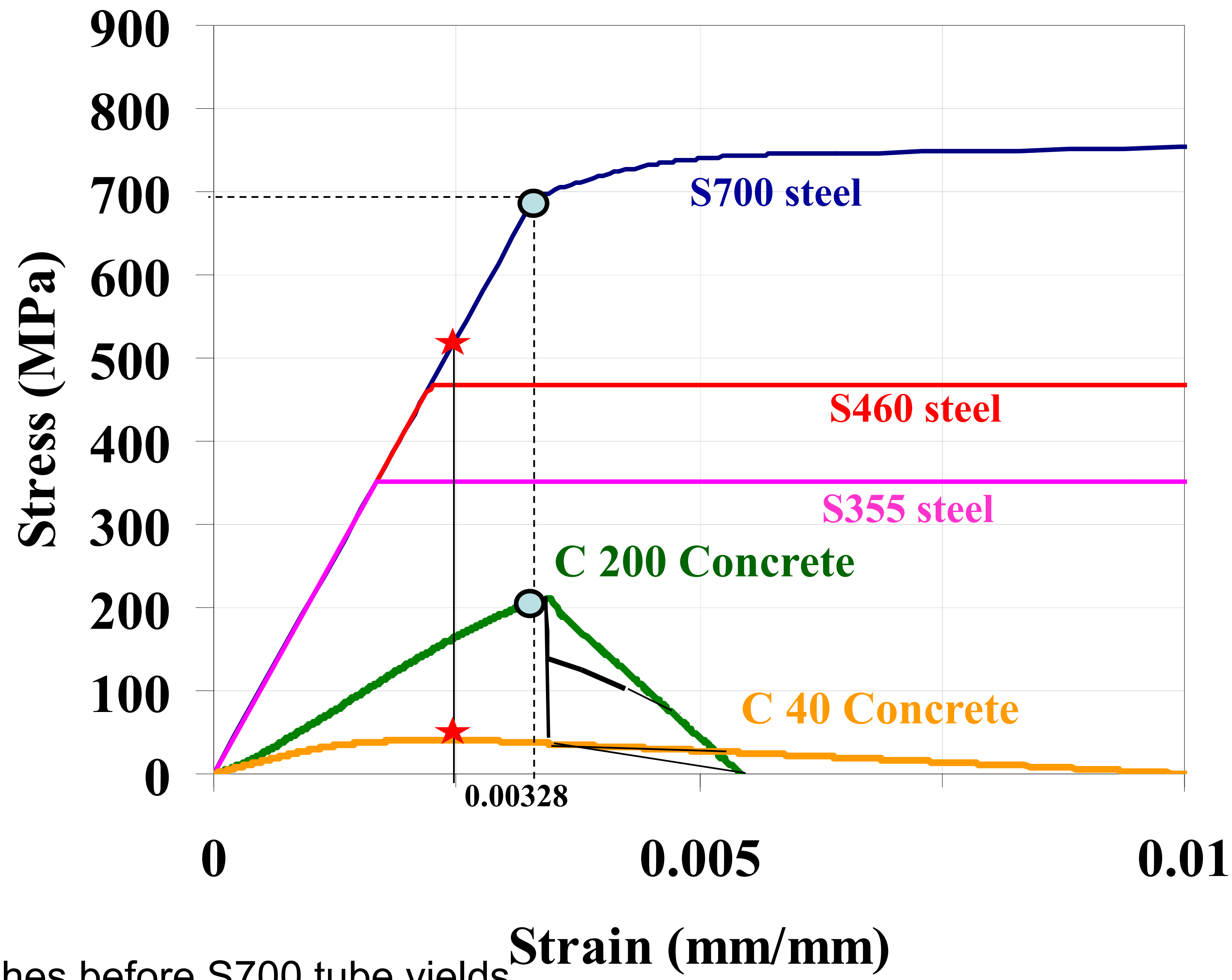

Steel yields before concrete crushes

Maximum Resistance
Is reached

Materials Compatibility of High Strength Steel and Concrete



Problem with high strength steel low strength concrete



★C40 concrete crushes before S700 tube yields

○ C200 concrete is compatible with S700 steel

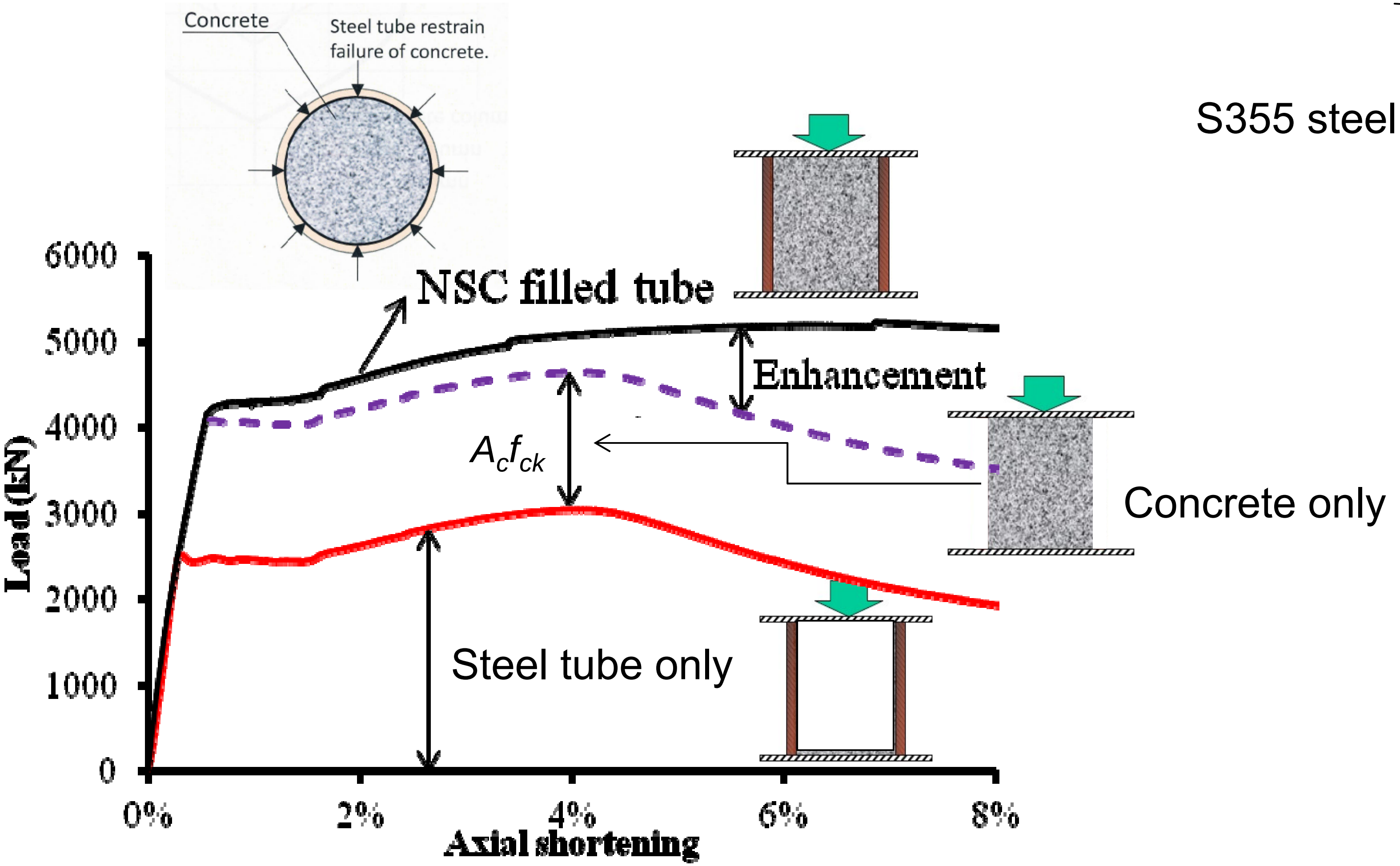
Design Recommendations to EC4

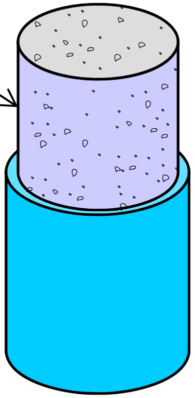
Material Compatibility between Steel grade and Concrete Class

	S235	S275	S355	S420	S460	S500	S550	S620	S690
C12/15	√	√	√	×	×	×	×	×	×
C16/20	√	√	√	×	×	×	×	×	×
C20/25	√	√	√	×	×	×	×	×	×
C25/30	√	√	√	√	×	×	×	×	×
C30/37	√	√	√	√	×	×	×	×	×
C35/45	√	√	√	√	√	×	×	×	×
C40/50	√	√	√	√	√	×	×	×	×
C45/55	√	√	√	√	√	√	×	×	×
C50/60	√	√	√	√	√	√	×	×	×
C55/67	√	√	√	√	√	√	×	×	×
C60/75	√	√	√	√	√	√	×	×	×
C70/85	√	√	√	√	√	√	√	×	×
C80/95	√	√	√	√	√	√	√	×	×
C90/105	√	√	√	√	√	√	√	×	×

Notes: “√” indicates compatible materials and “×” is not recommended.

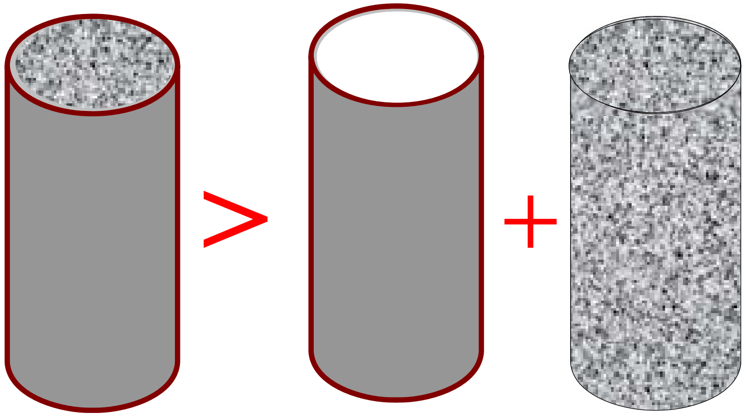
Confinement effect on Concrete compressive Resistance





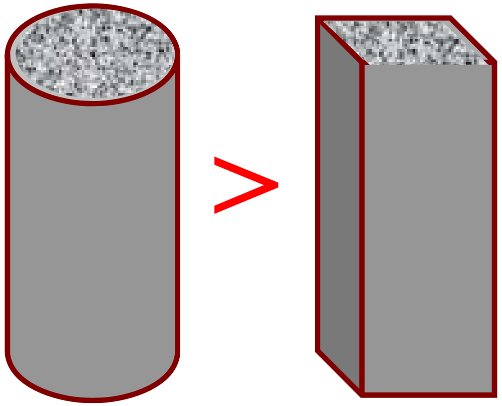
Advantages of CFSTs

2>1+1



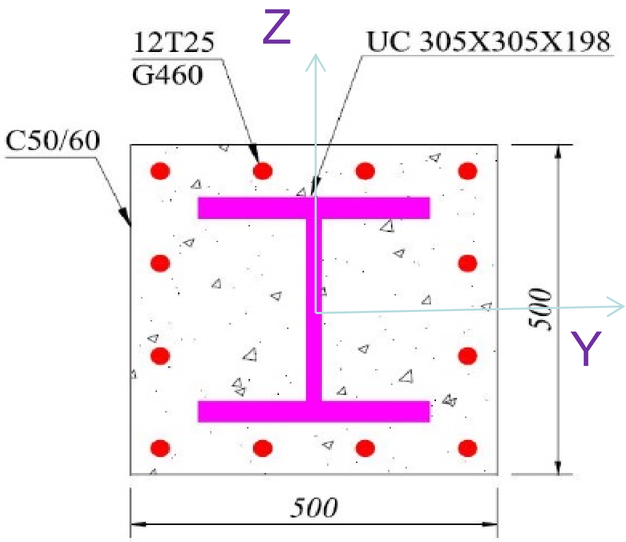
Circular

Eurocodes allow higher compressive strength of concrete to be used in the design if it is confined

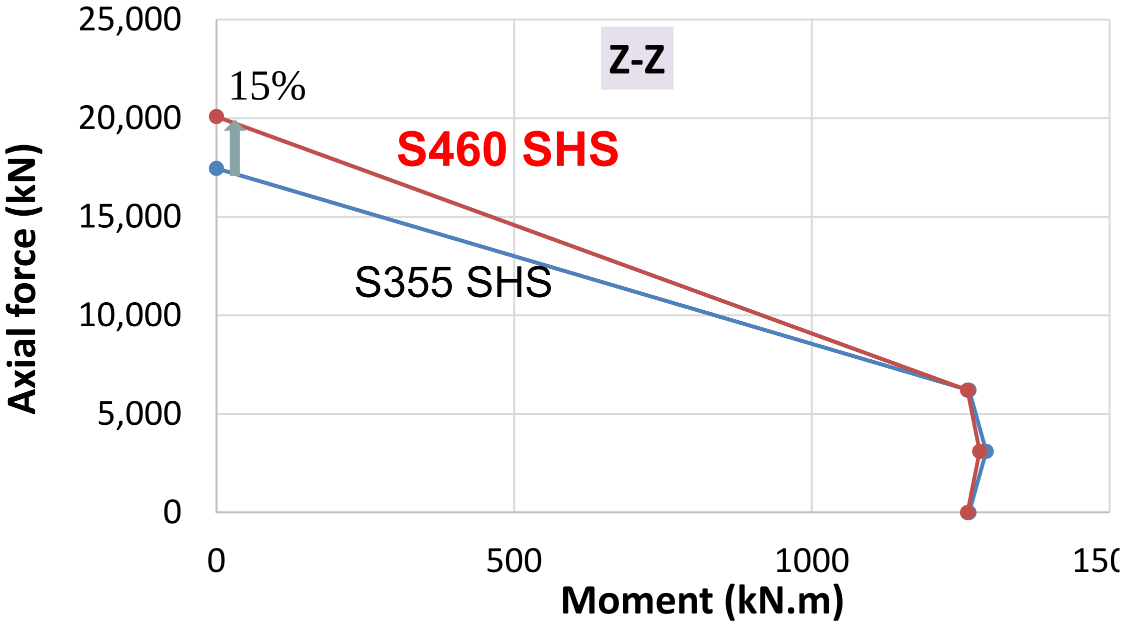


Advantage of S460 Steel

Concrete Encased H-Sections– Moment + Compression Interaction Curves

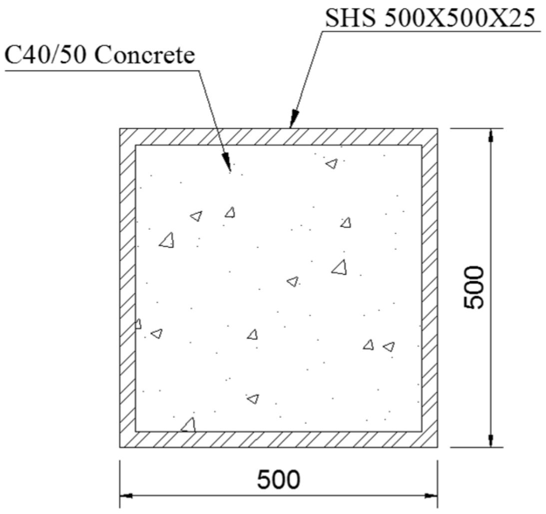


Concrete Encased H-Sections

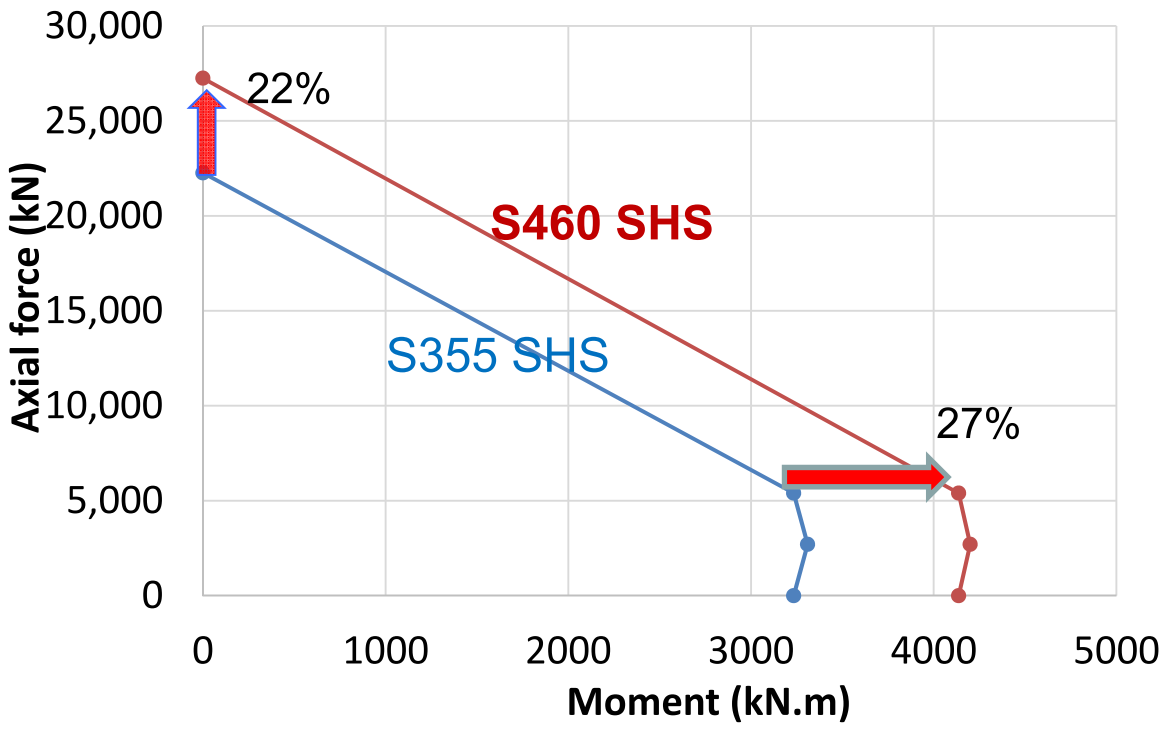


- Cross section resistance increases with increasing steel grade, due to higher steel strength.
- For pure compression, the increase is about 15%.
- Not too effective if moment dominates

Cross section resistance of concrete filled tube – Moment + Compression Interaction Curves

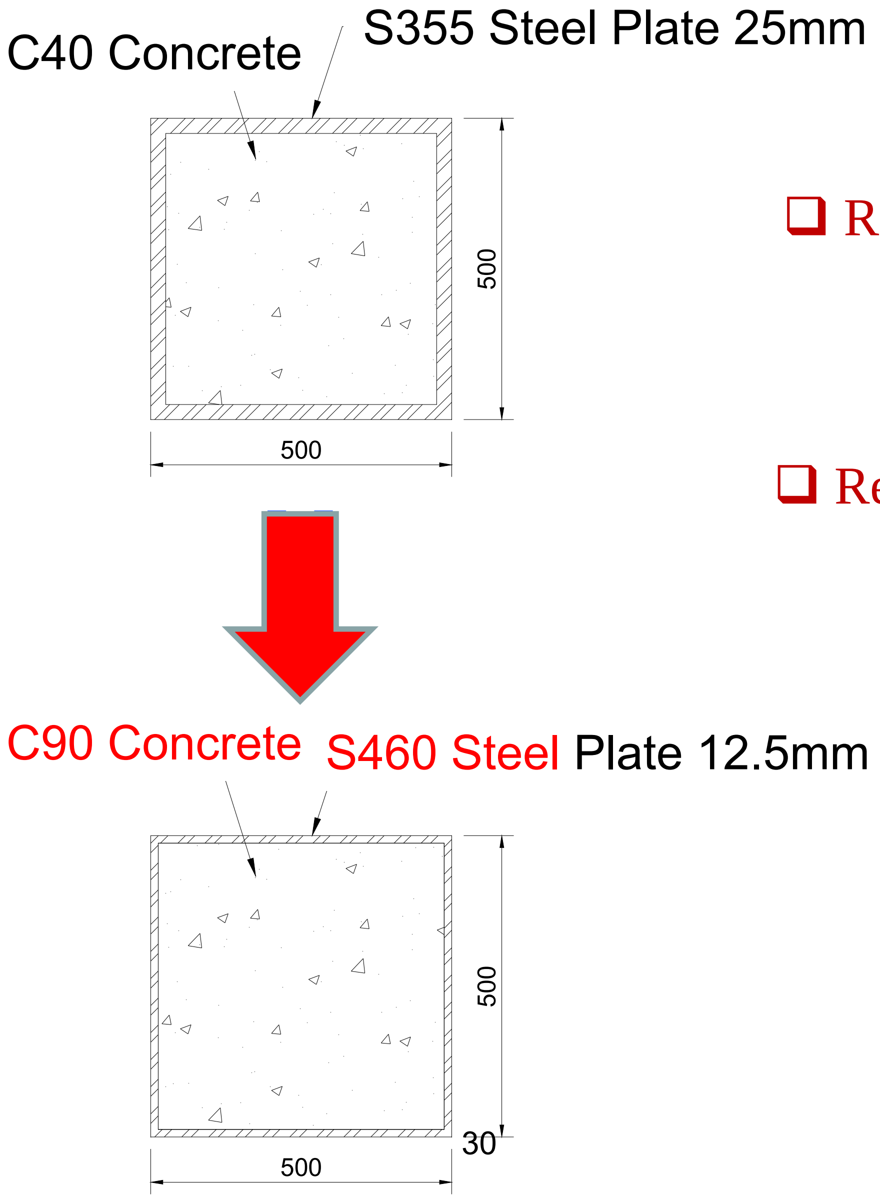


concrete filled tube



- Increase in compression and bending resistances >22%
- CFTs are more economical to resist high axial force and moments.
- No re-bars work

Comparison based on same buckling resistance with column height 4.2m



C40 Concrete

S355 Steel Plate 25mm

C90 Concrete

S460 Steel Plate 12.5mm

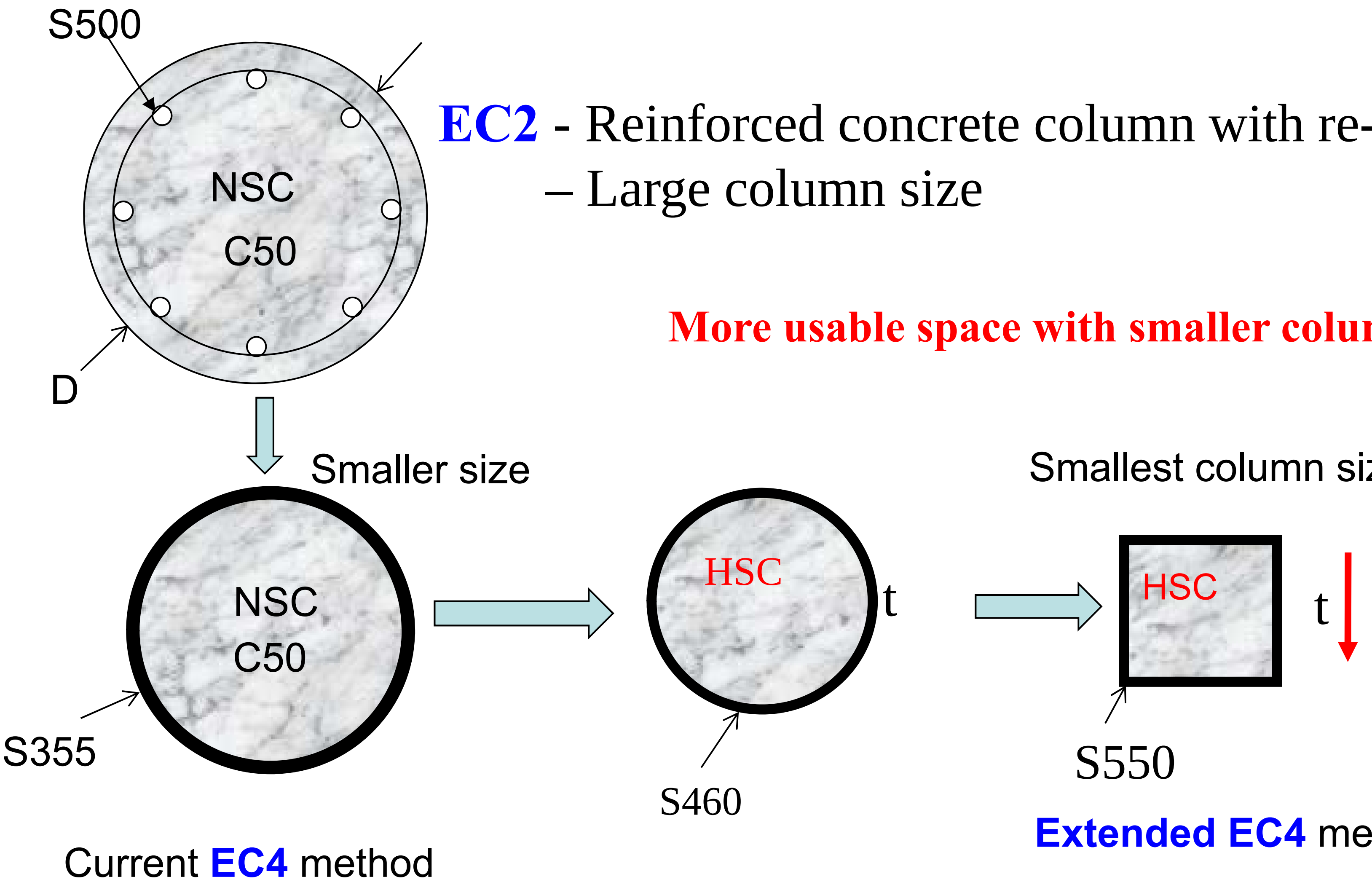
- Reduction of tube thickness: 50%

$$\mu_t = \frac{25-12.5}{25}\times 100\% = 50\%$$

- Reduction of butt weld: 25%

$$\mu_w = \left(\frac{25-12.5}{25}\right)^2 \times 100\% = 25\%$$

Application of high strength materials for tall building construction



EC2 - Reinforced concrete column with re-bars
– Large column size

More usable space with smaller column size

Smaller size

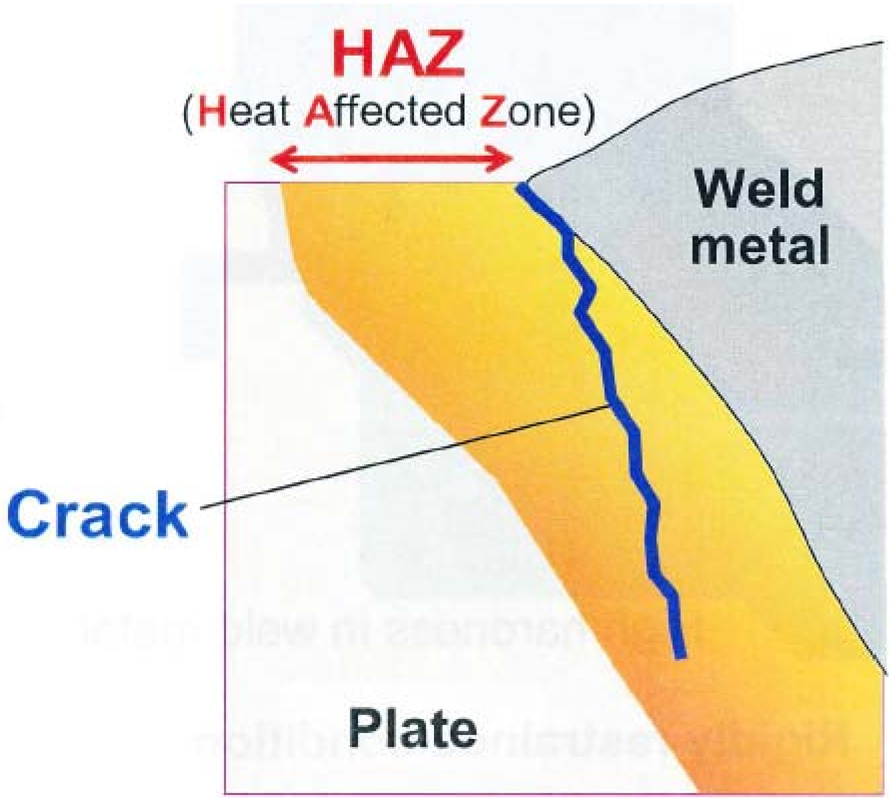
Smallest column size

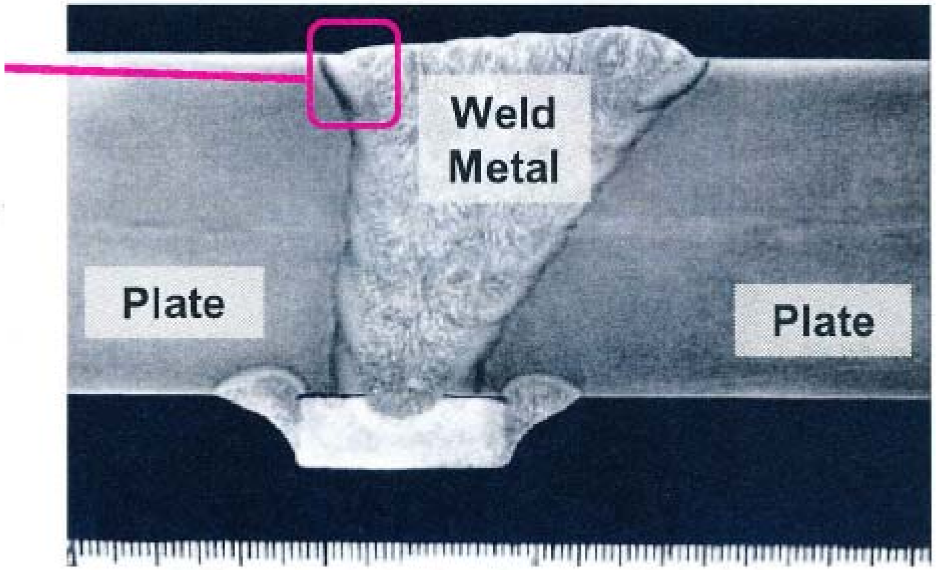
Current **EC4** method

Extended EC4 method

Problems of Welding Very Thick Plate

HAZ hardening
High residual stress
Cold Cracking
Be careful of high heat input welding!

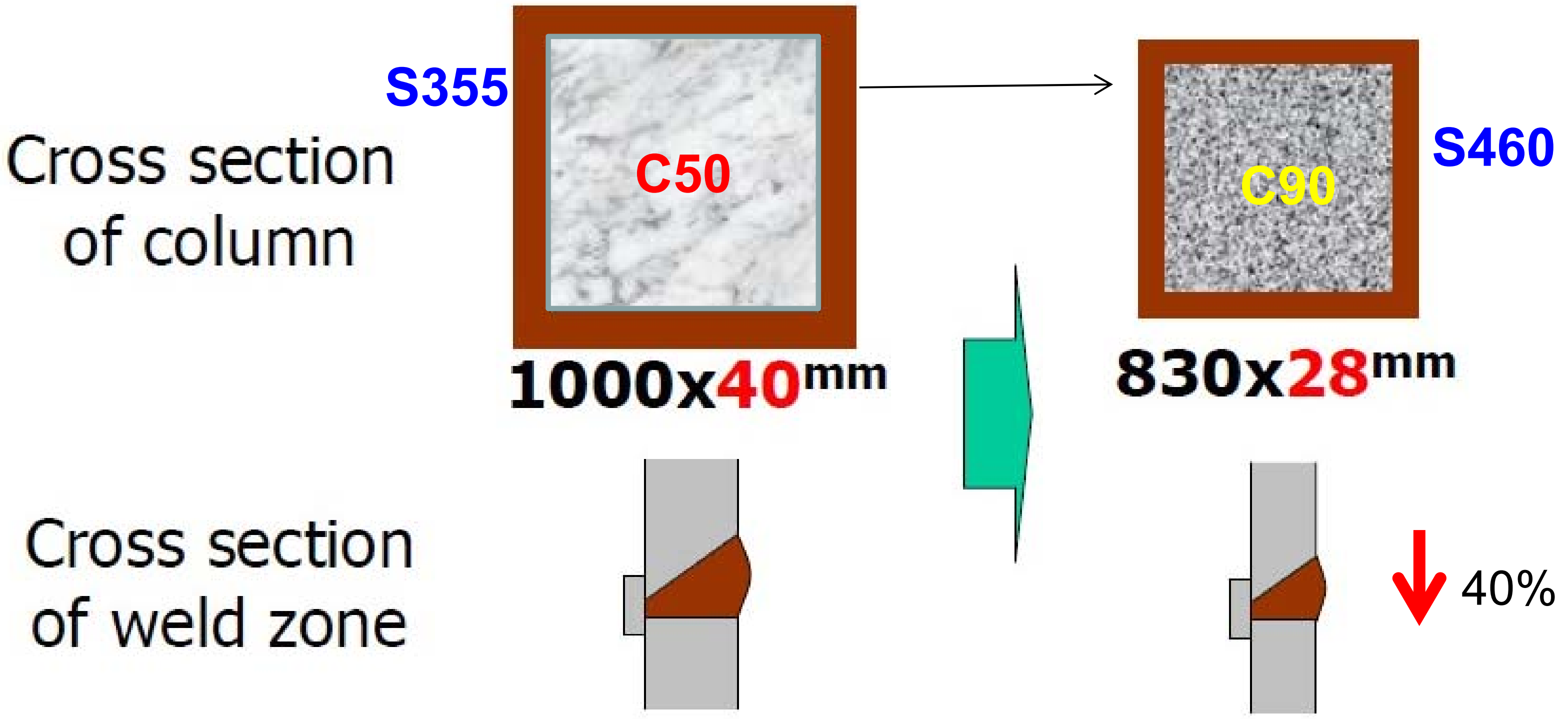




Cross section of a welded joint

Use of Thinner Tube Improves Welding Productivity

Use of CFST with high strength steel



Thickness of tube : 40mm ⇒ 28mm

Welding operation : 32-pass ⇒ 18-pass

CFTs with Ultra high strength cement composite & High Strength Steel

- **Liew, J Y R and Xiong DX, Ultra-high strength concrete filled composite columns for multi-storey building construction, Advances in Structural Engineering, 15, no. 9 (2012): 1487-1503.**

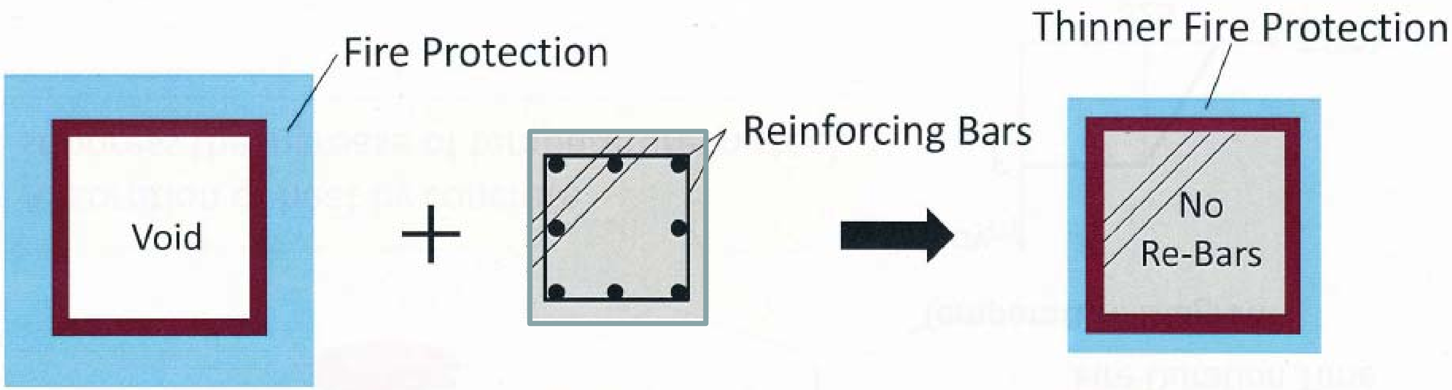
- **Liew J Y R, Xiong, MX and Xiong DX, Design of high strength concrete filled tubular columns for tall buildings, International Journal of High-Rise Buildings, 2014, Vol 3, No 3, 1-7**

Reduction Factor Applied to High Strength Concrete

Type of column		Compressive cylinder strength of concrete		
		≤50 N/mm^2	**51 to 90 N/mm^2**	**>90 N/mm^2**
Axially loaded circular cross section	Nos.	295	130	44
	Test/EC4 ≥ 1	66.8% (99.3%)	[66.9%] {97.7%}	[100%] {100%}
	Av.	1.068 (1.354)	[1.062] {1.383}	[1.415] {1.838}
	St. Dev.	0.136 (0.168)	[0.132] {0.190}	[0.291] {0.391}
Axially loaded circular column	Nos.	383	60	22
	Test/EC4 ≥ 1	85.9% (97.4%)	[83.3%] {98.3%}	[100%] {100%}
	Av.	1.186 (1.388)	[1.075] {1.339}	[1.319] {1.633}
	St. Dev.	0.246 (0.267)	[0.121] {0.162}	[0.254] {0.321}
Circular beam-column	Nos.	240	66	46
	Test/EC4 ≥ 1	82.1% (98.8%)	[81.8%] {98.5%}	[80.4%] {93.5%}
	Av.	1.192 (1.352)	[1.136] {1.356}	[1.523] {1.674}
	St. Dev.	0.217 (0.237)	[0.189] {0.216}	[0.728] {0.719}
Axially loaded rectangular cross section	Nos.	282	63	39
	Test/EC4 ≥ 1	80.1% (99.6%)	[90.5%] {96.8%}	[100%] {100%}
	Av.	1.122 (1.287)	[1.118] {1.330}	[1.239] {1.409}
	St. Dev.	0.150 (0.196)	[0.117] {0.168}	[0.159] {0.166}
Axially loaded rectangular column	Nos.	101	40	12
	Test/EC4 ≥ 1	62.4% (94.1%)	[77.5%] {95.0%}	[100%] {100%}
	Av.	1.059 (1.220)	[1.099] {1.321}	[1.246] {1.485}
	St. Dev.	0.140 (0.172)	[0.140] {0.177}	[0.242] {0.261}
Rectangular beam-column	Nos.	160	23	27
	Test/EC4 ≥ 1	73.1% (98.1%)	[87.0%] {100%}	[85.2%] {100%}
	Av.	1.107 (1.338)	[1.128] {1.461}	[1.147] {1.364}
	St. Dev.	0.279 (0.341)	[0.102] {0.148}	[0.177] {0.177}

value1 is based on the characteristic strengths of steel and concrete; (value2) is based on design strengths; [value3] is based on characteristic strengths with reduction factor η for concrete; {value4} is based on design strengths with reduction factor η for concrete.

Fire Resistance Performance



Steel Column

Small Heat Capacity

Fire Protection is necessary

RC Column

Larger Heat Capacity

Reinforcing Bars Restrain
Load Support Area of Concrete.

CFT Column

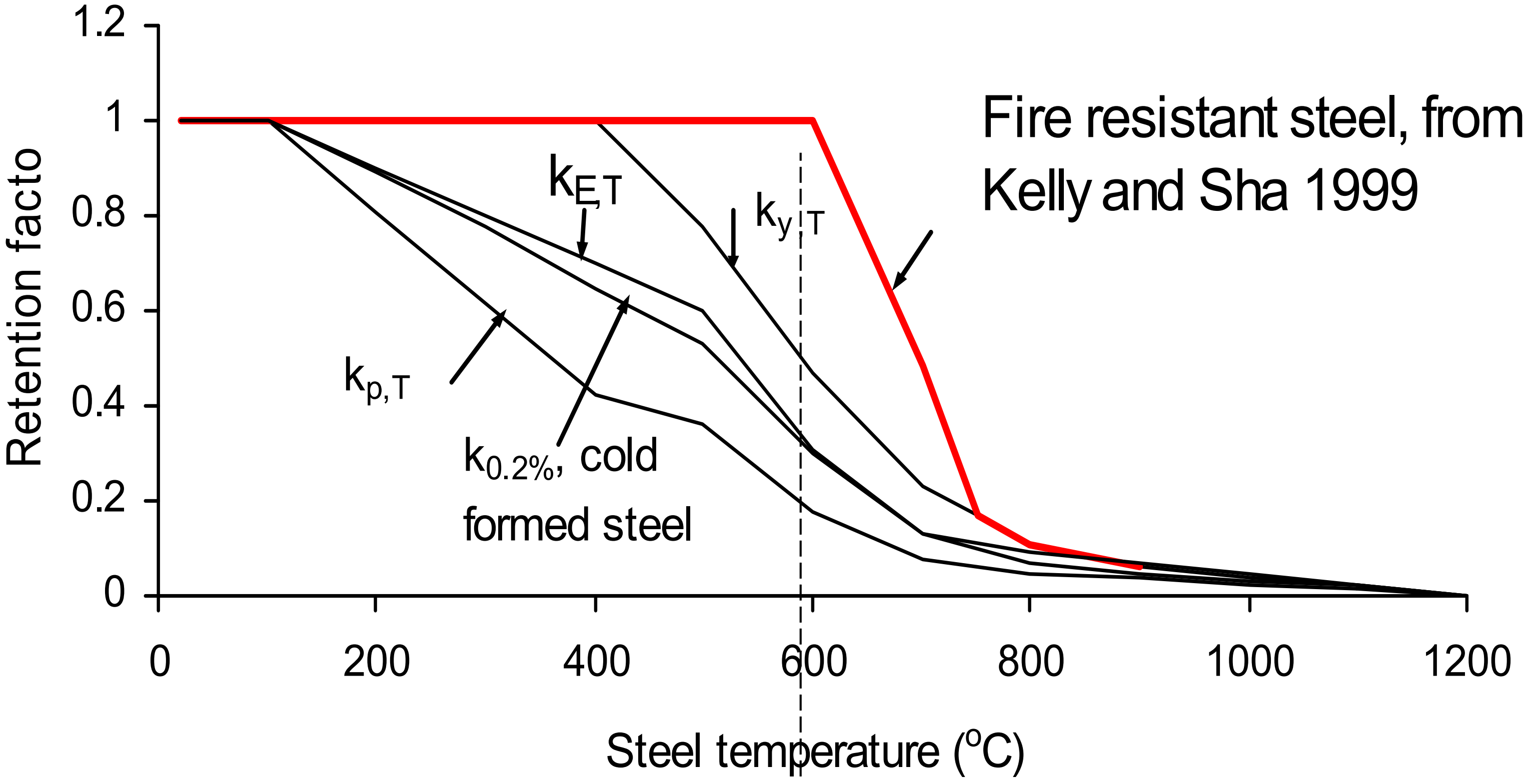
Smaller Fire Protection volume

Steel Tube Restrain
Load Support Area of Concrete.

Thickness of Fire Protection

	2 Hour Fire-Resistance	**3** Hour Fire-Resistance
Steel column	45mm	60mm
CFT column	**20mm**	**30mm**

Strength Retention of Steel in Fire



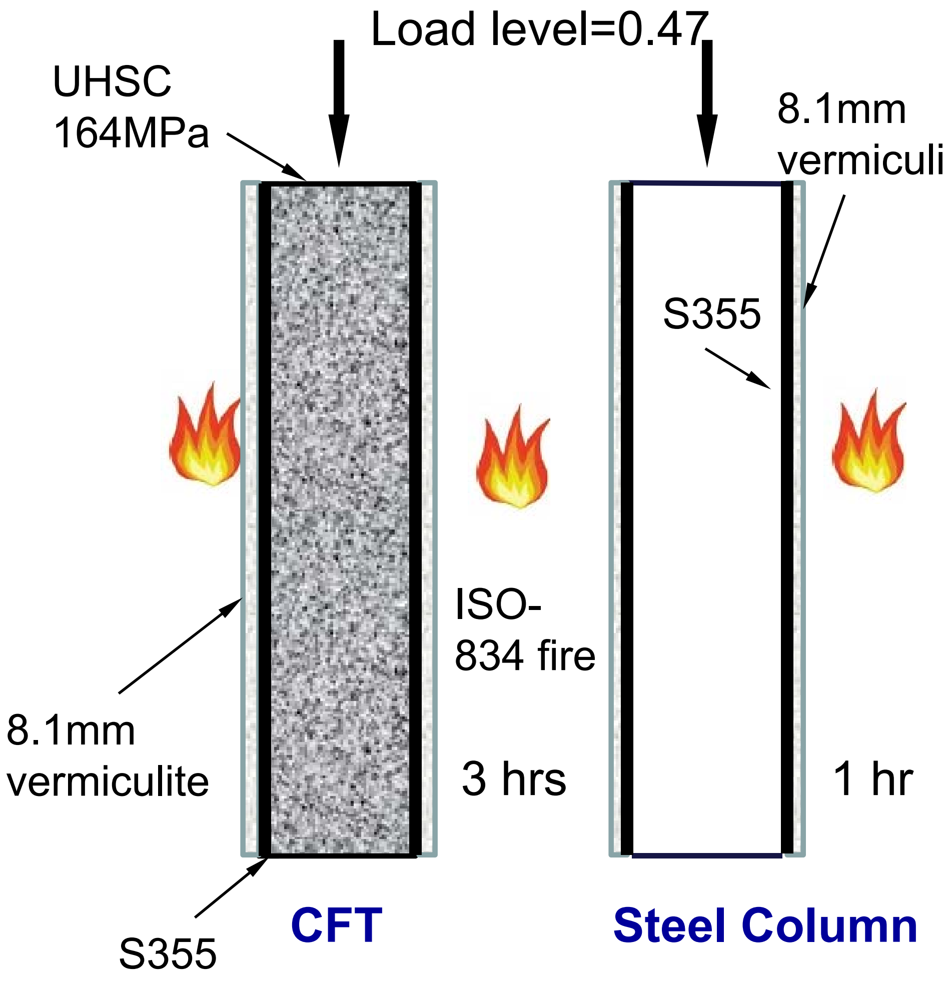
Effective yield strength of steel starts to reduce at 400^{o}C
Young modulus of steel starts to reduce at 150^{o}C

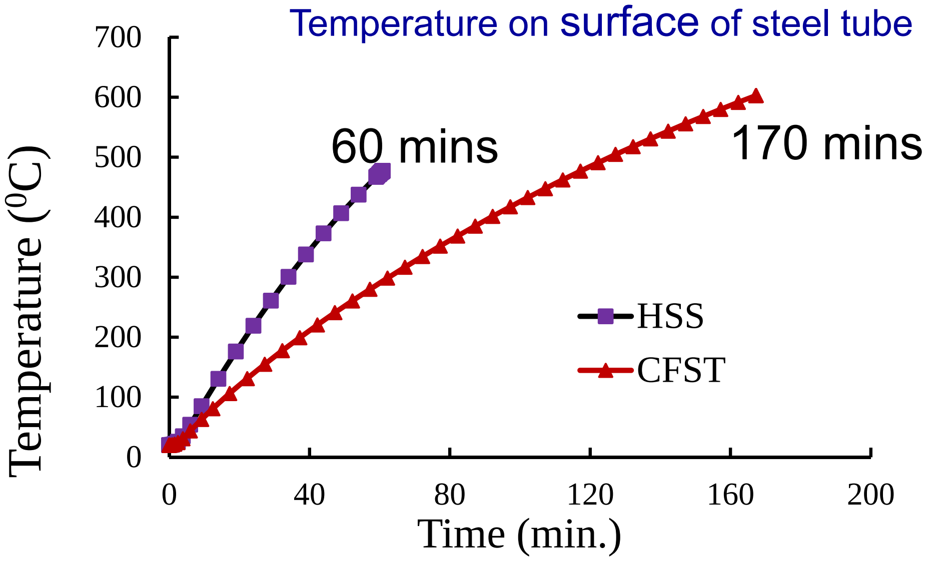
Fire Resistance Performance of Circular Column

Circular CFST Vs. Circular HSS

Same tube size CHS 219.1X16

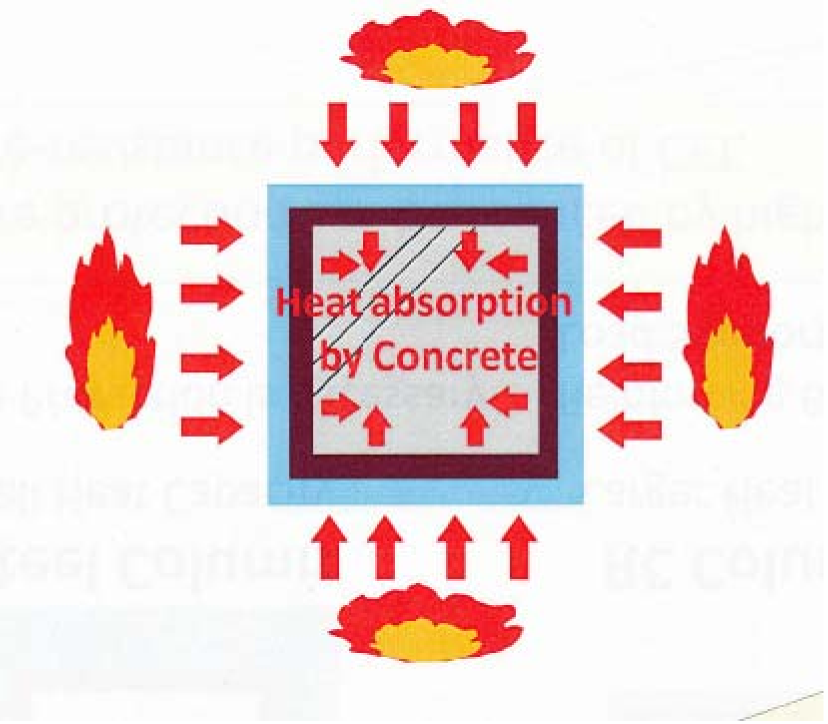
Section factor Am/V=18m^{-1}

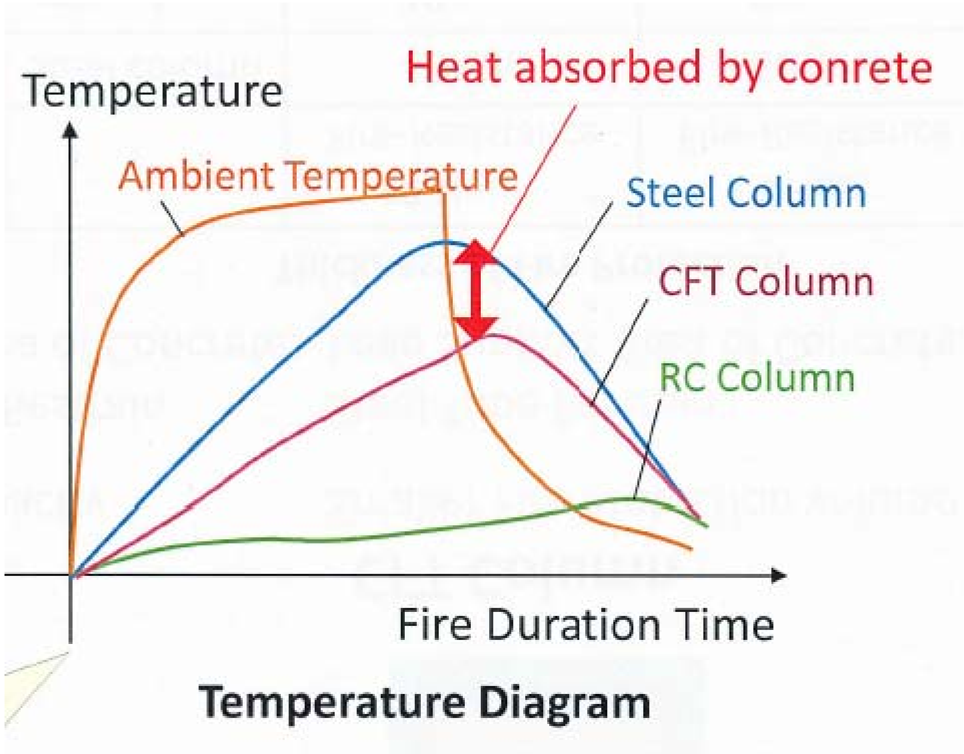




Fire Performance of CFT

- Heat Absorbed by the concrete core reduces the temperature of the external steel tube
- It requires less fire protection than steel tube

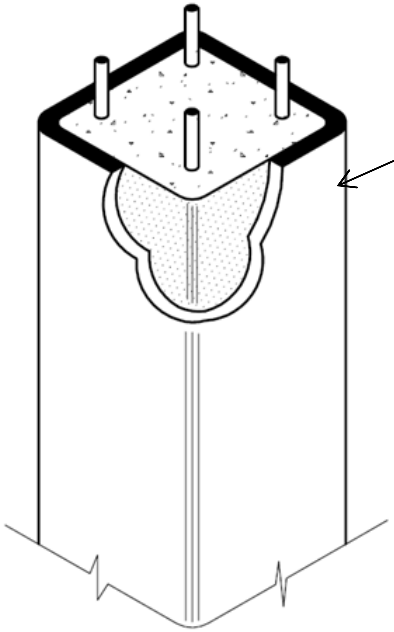




Temperature Diagram

CFTs without External Fire Protection

Filled hollow sections will need to contain reinforcement in the mix in order to minimise column dimensions and to sustain the required fire limit state design loads for fire resistance periods of 60 minutes or more.



Sacrifice the steel tube in fire.
RC column will resist the design load in fire

Fire resistant design of composite columns based on EC4 (EN 1994-1-2:2005)

Simplified table in EC4

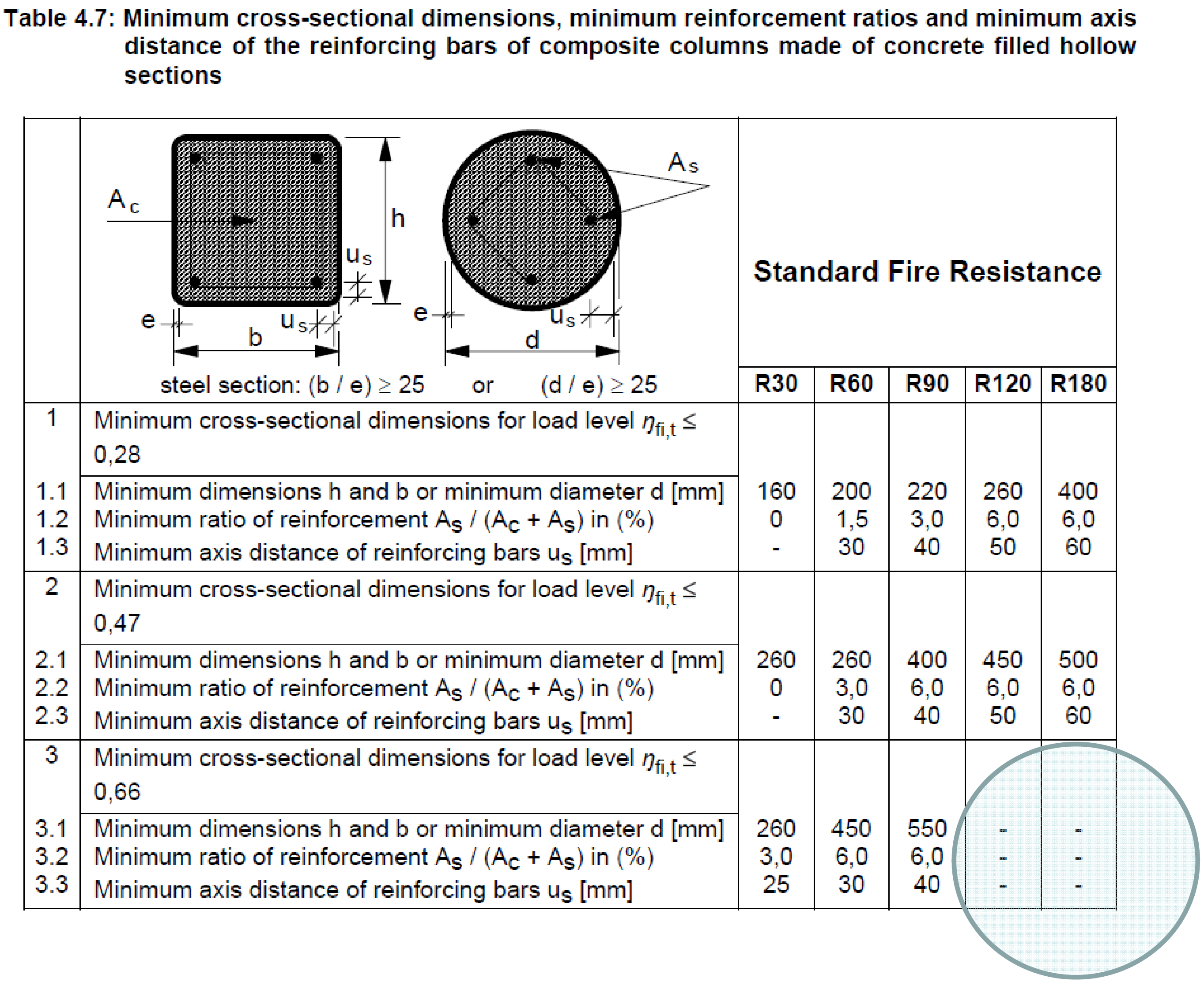


Table 4.7: Minimum cross-sectional dimensions, minimum reinforcement ratios and minimum axis distance of the reinforcing bars of composite columns made of concrete filled hollow sections

	steel section: $(b / e) \geq 25$ or $(d / e) \geq 25$	Standard Fire Resistance				
		R30	R60	R90	R120	R180
1	Minimum cross-sectional dimensions for load level $\eta_{fi,t} \leq 0{,}28$					
1.1	Minimum dimensions h and b or minimum diameter d [mm]	160	200	220	260	400
1.2	Minimum ratio of reinforcement $A_s / (A_c + A_s)$ in (%)	0	1,5	3,0	6,0	6,0
1.3	Minimum axis distance of reinforcing bars u_s [mm]	-	30	40	50	60
2	Minimum cross-sectional dimensions for load level $\eta_{fi,t} \leq 0{,}47$					
2.1	Minimum dimensions h and b or minimum diameter d [mm]	260	260	400	450	500
2.2	Minimum ratio of reinforcement $A_s / (A_c + A_s)$ in (%)	0	3,0	6,0	6,0	6,0
2.3	Minimum axis distance of reinforcing bars u_s [mm]	-	30	40	50	60
3	Minimum cross-sectional dimensions for load level $\eta_{fi,t} \leq 0{,}66$					
3.1	Minimum dimensions h and b or minimum diameter d [mm]	260	450	550	-	-
3.2	Minimum ratio of reinforcement $A_s / (A_c + A_s)$ in (%)	3,0	6,0	6,0	-	-
3.3	Minimum axis distance of reinforcing bars u_s [mm]	25	30	40	-	-

No guidance for large size columns

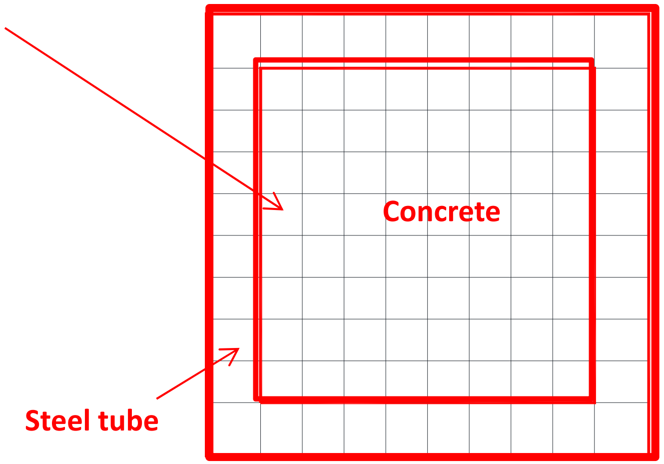
Fire resistant design of composite columns based on EC4 (EN 1994-1-2:2005): Fire Engineering Calculation Method

$$N_{fi,Rd} = \chi N_{fi,pl,Rd}$$

$$N_{fi,pl,Rd} = \sum_{j} \left(\frac{A_{a,\theta} f_{ay,\theta}}{\gamma_{M,fi,a}} + \frac{A_{c,\theta} f_{c,\theta}}{\gamma_{M,fi,c}} \right)$$

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}_\theta^2}}$$

Perform heat transfer analysis to, determine the temperature distribution , θ_i



Where:

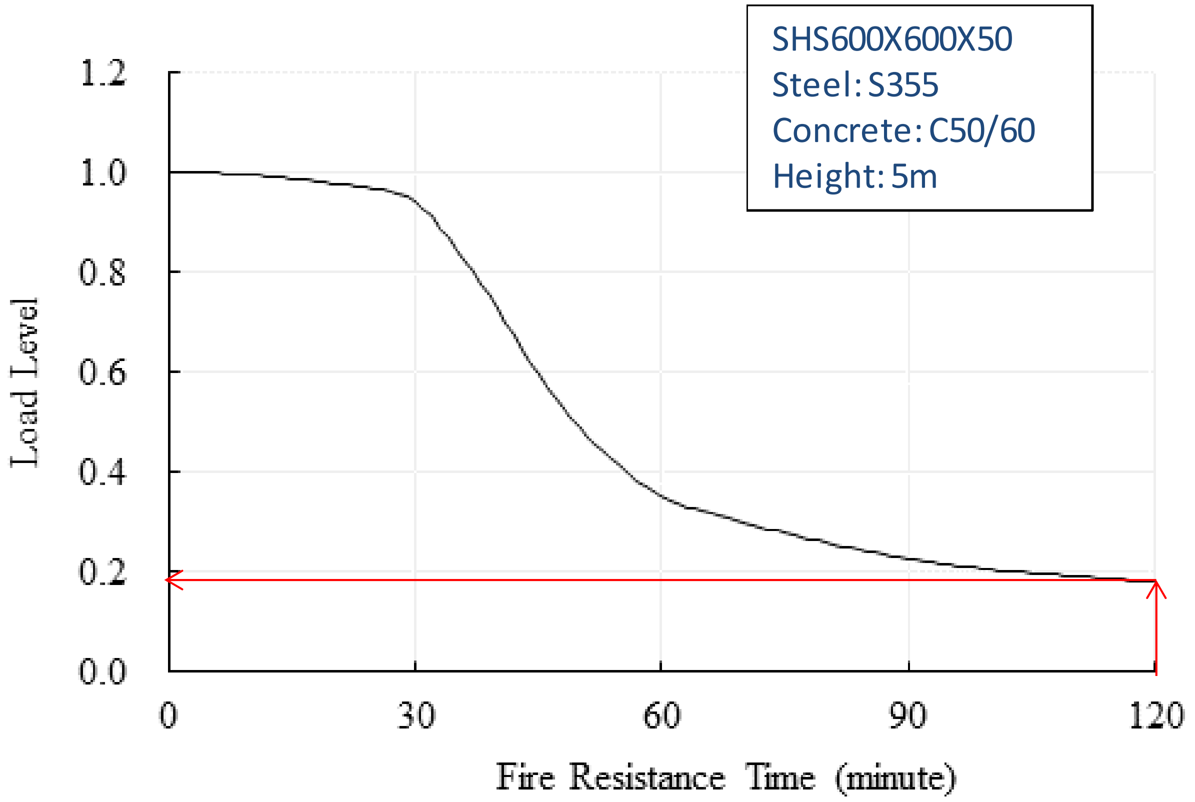
$$\Phi = 0.5\left[1 + 0.49\left(\bar{\lambda}_\theta - 0.2\right) + \bar{\lambda}_\theta^2\right], \bar{\lambda}_\theta = \sqrt{N_{fi,pl,R} / N_{fi,cr}}$$

$$N_{fi,cr} = \frac{\pi^2 (EI)_{fi,eff}}{l_\theta}$$

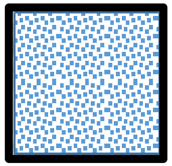
$$(EI)_{fi,eff} = \sum_{j} \left(\varphi_{a,\theta} E_{a,\theta} I_{a,\theta}\right) + \sum_{k} \left(\varphi_{c,\theta} E_{c,\theta} I_{c,\theta}\right) + \sum_{m} \left(\varphi_{s,\theta} E_{s,\theta} I_{s,\theta}\right)$$

Section discretized, temperature calculated for each element, temperature-dependent material properties applied to each element!

Fire Resistance Versus Load Level



SHS600X600X50
Steel: S355
Concrete: C50/60
Height: 5m



Load Level

$$\mu_0 = \frac{E_{fi.d}}{R_{fi.d.0}}$$

$$\frac{\text{Design effect in fire}}{\textbf{Rresistance}\text{ at ambient temperature}}$$

Ambient temperature strength design

γ_G = 1,35 Permanent loads;

$\gamma_{Q.1}$ = 1,5 Combination factor; variable loads

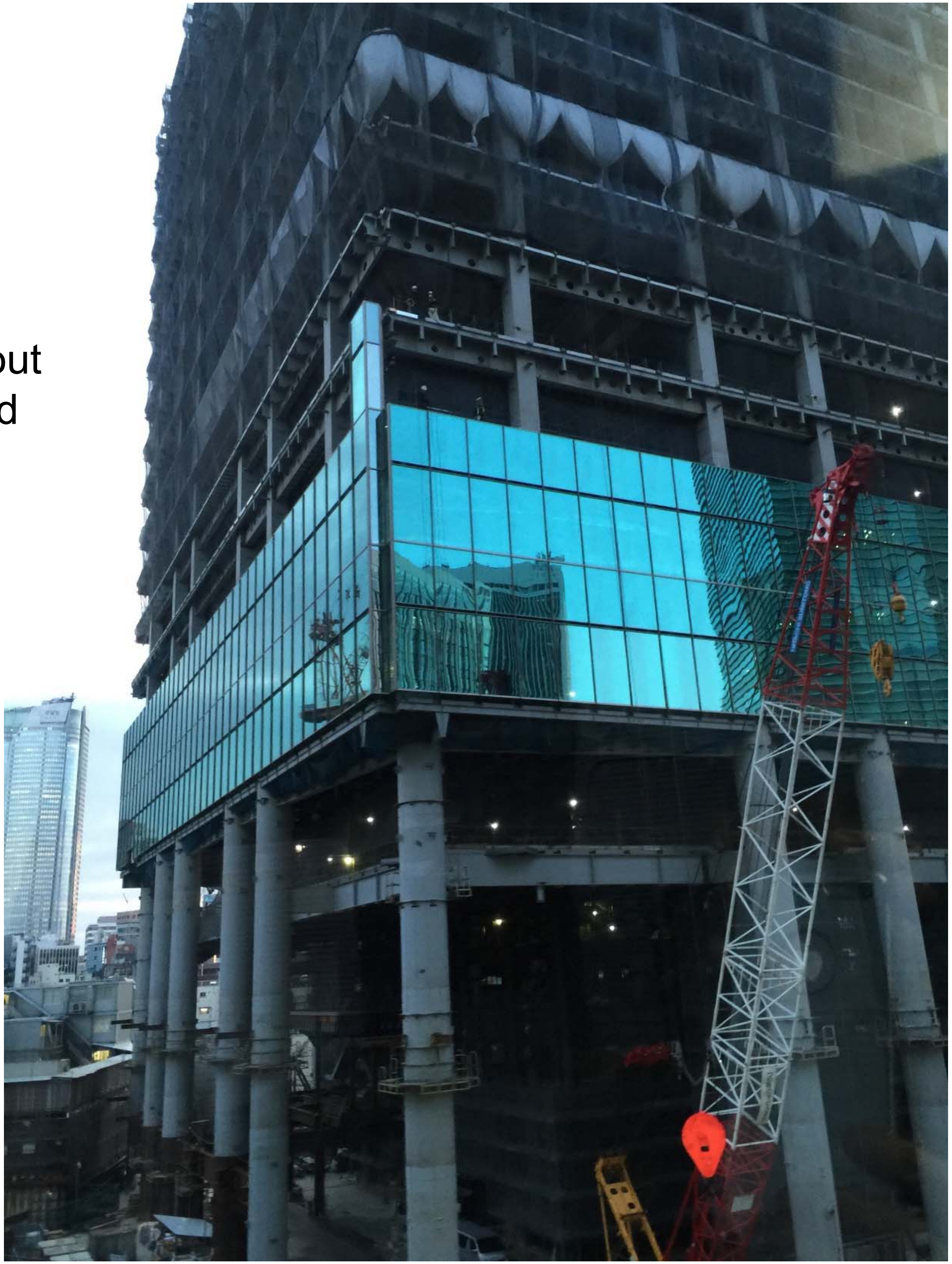
In Fire limit state

γ_{GA} = 1,0 Permanent loads; accidental design situations

$\psi_{1.1}$ = 0,5 Combination factor; variable loads, offices

$Q_{k.1}/G_k$	1	2	3	4
η_{fi}	0,53	0,46	0,43	0,41

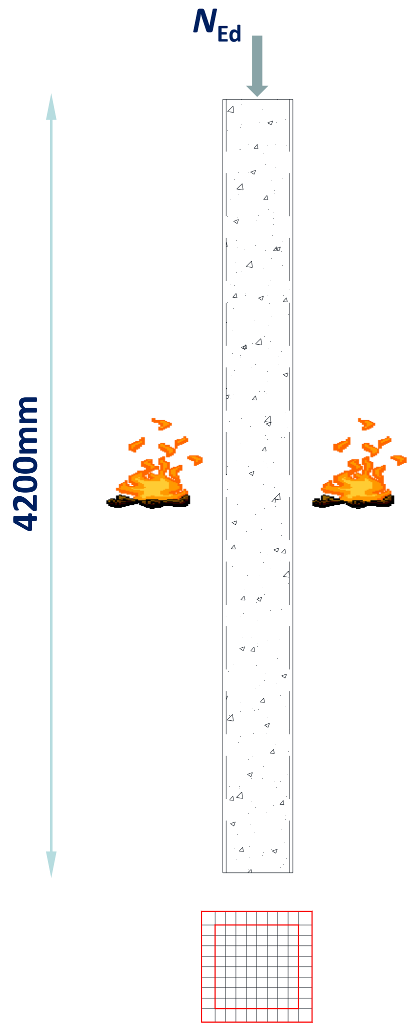
Exposed Concrete Filled Tubes without Fire Protection in Japan because load level is low



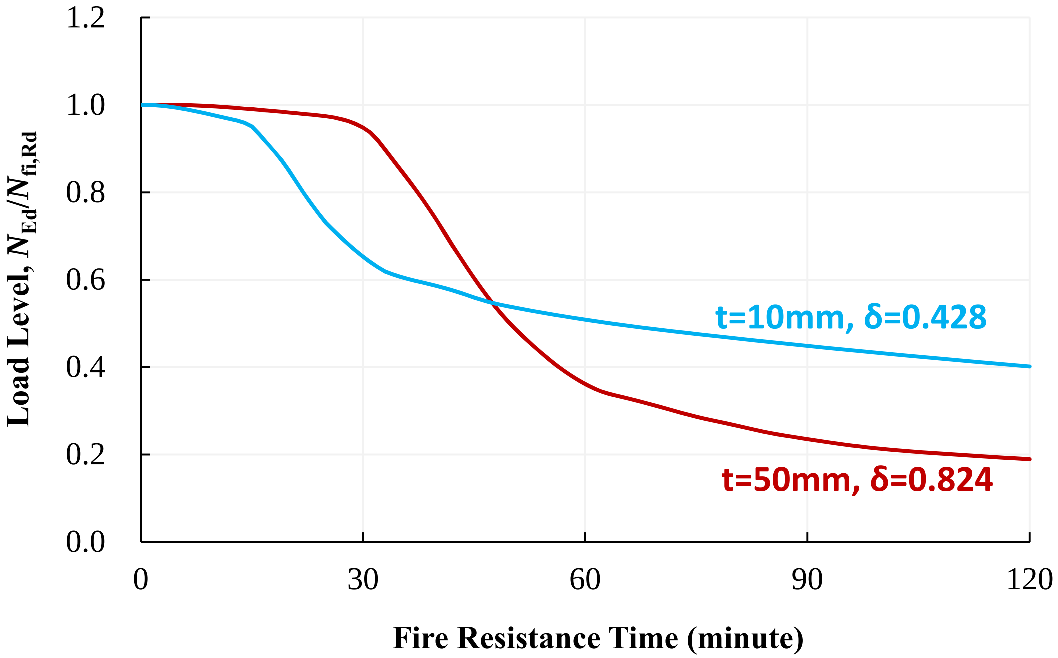
Fire resistant design of composite columns based on EC4 (EN 1994-1-2:2005)

☐ Simple Calculation Models (Case Study)

Fire protection is not necessary when the load level and steel contribution ratio, δ , are low!

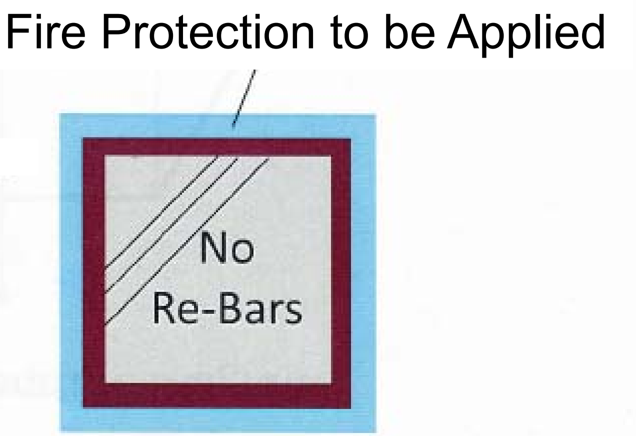


SHS600X600
S355, C50/60



t = plate thickness

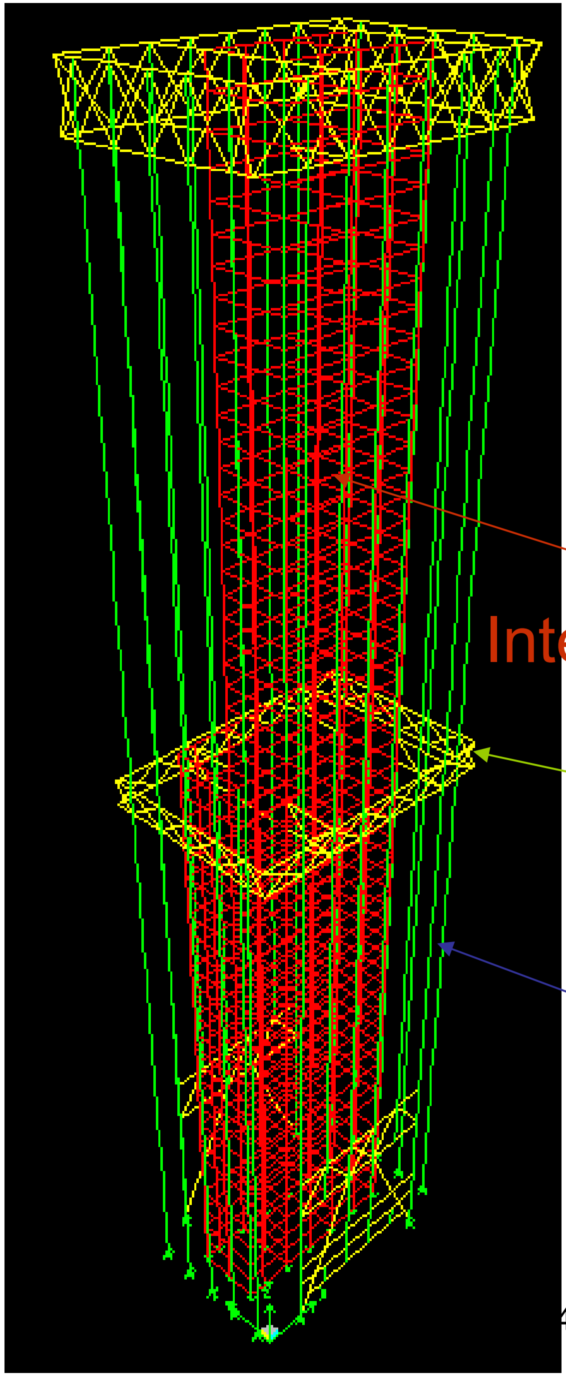
For common buildings not designed for earthquake loads and typical load level between 0.4 to 0.6

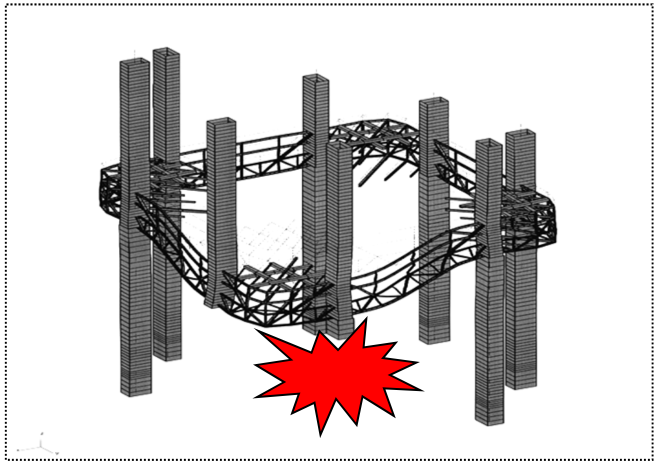


Thickness of Fire Protection

	2 Hour Fire-Resistance	**3** Hour Fire-Resistance
Steel column	45mm	60mm
CFT column	**20mm**	**30mm**

Progressive Collapse due to Accidental Loads – impact, blast, fire etc



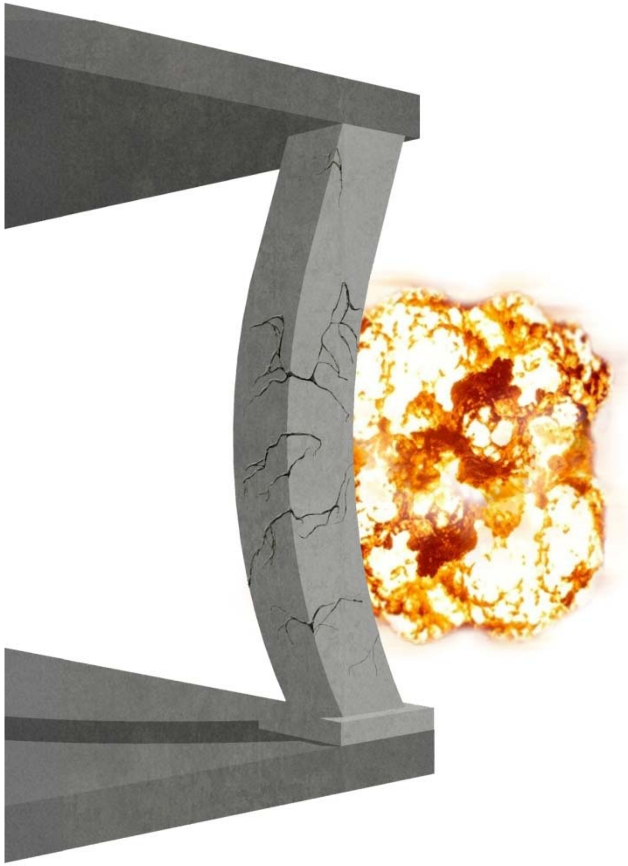


Internal Core

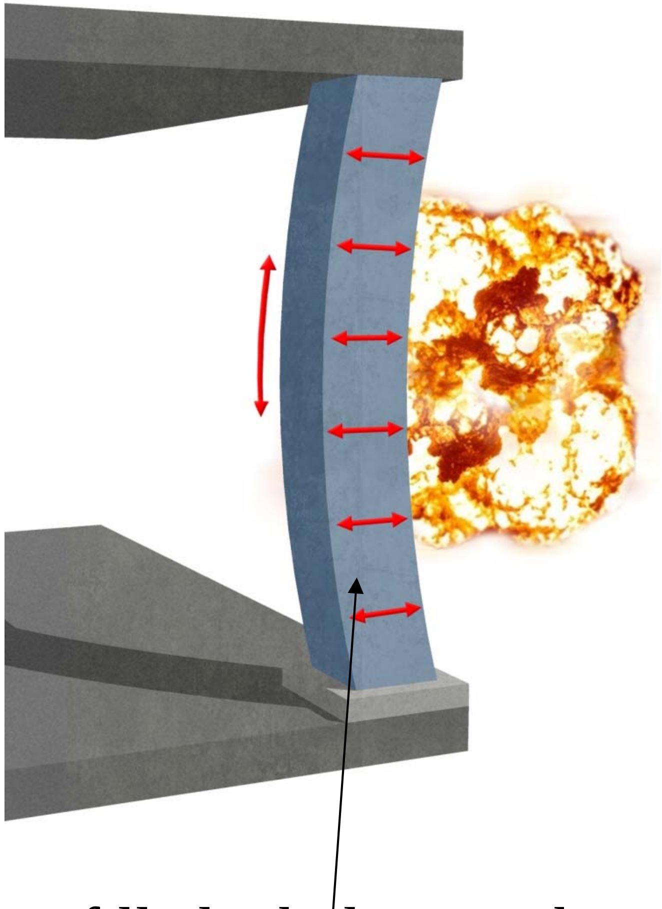
Belt and outrigger

Exterior columns

Columns Subject to Blast



Conventional RC Columns– Cracks and spalling; may involve flying debris

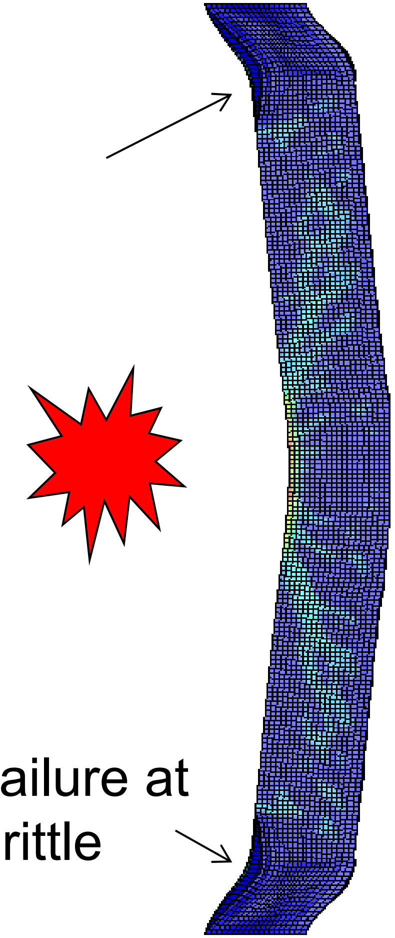


Concrete filled tubular member-
Concrete is confined

Columns subject to Blast Load

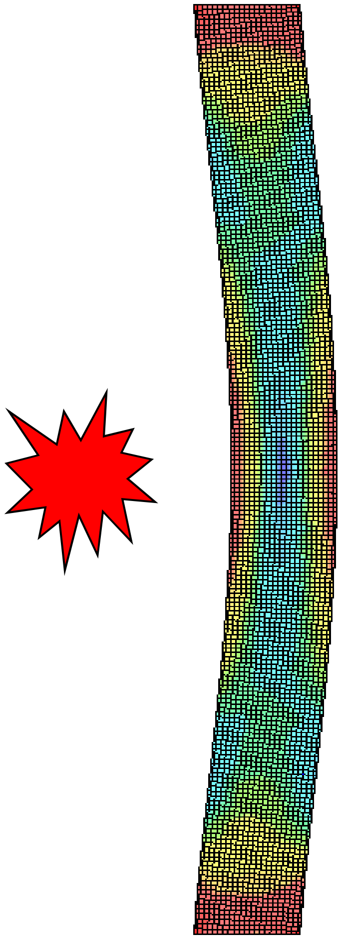
Deformed modes at 0.004 sec after application of blast overpressure

RC Column



Shear Failure at ends - brittle

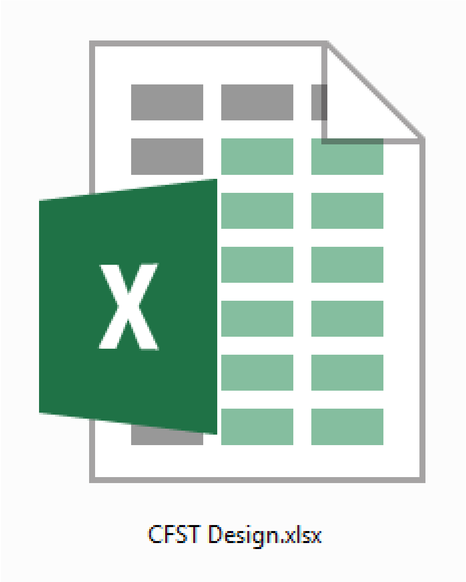
Concrete-filled composite column



Flexural Mode –ductile deformation
No failure

Design for Concrete Filled Steel Tubular (CFST) Column according to EN 1994-1-1 Using Spreadsheet developed by NUS

Database for Steel Sections

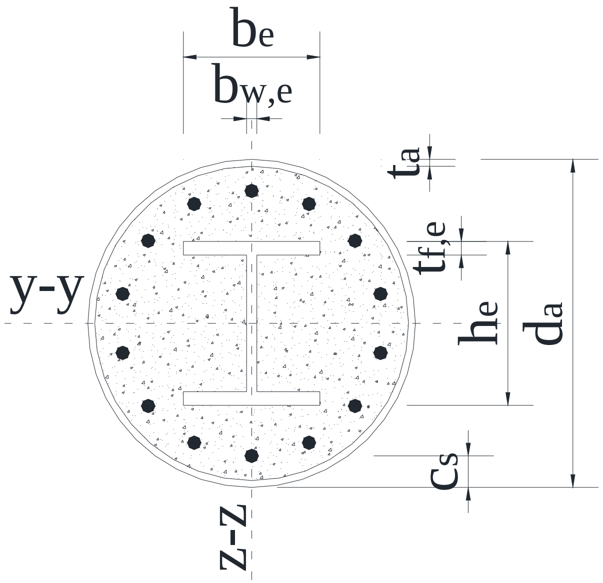


Main Program

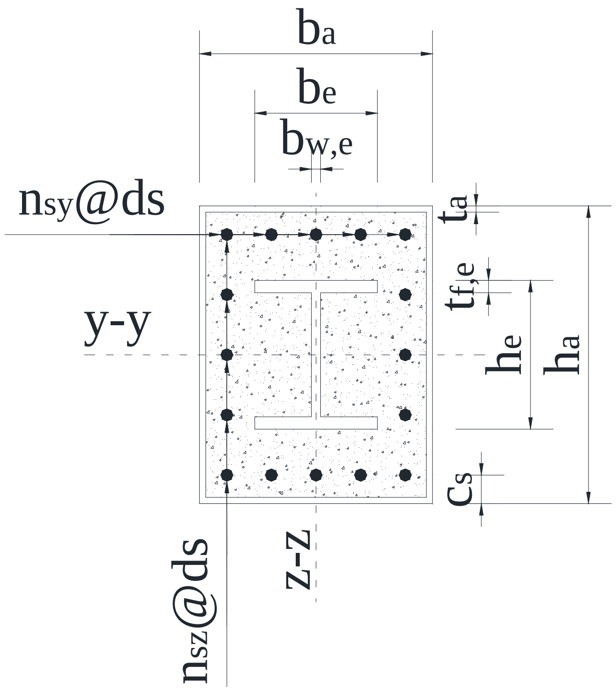
The users must open both files!

Applicable to:

Circular CFST



Rectangular CFST



Limit to:

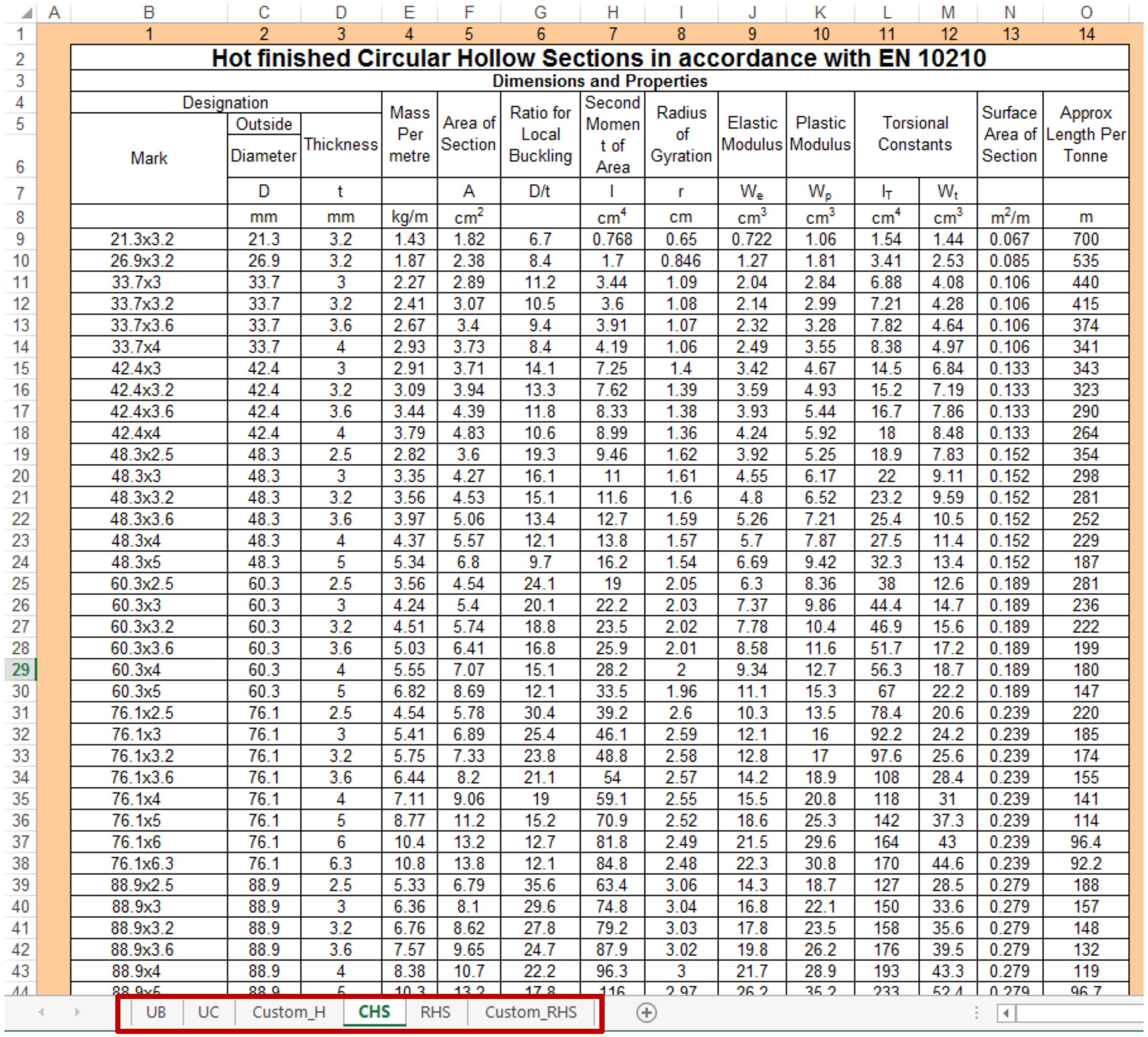
Steel grade: S235 ~ S550

Concrete grade: C20/25 ~ C90/105

Standard Steel Sections

SS.xls

The database for the hot-finished sections can be supplemented with sections from American, China, Japan, India, etc.



Hot finished Circular Hollow Sections in accordance with EN 10210

Dimensions and Properties

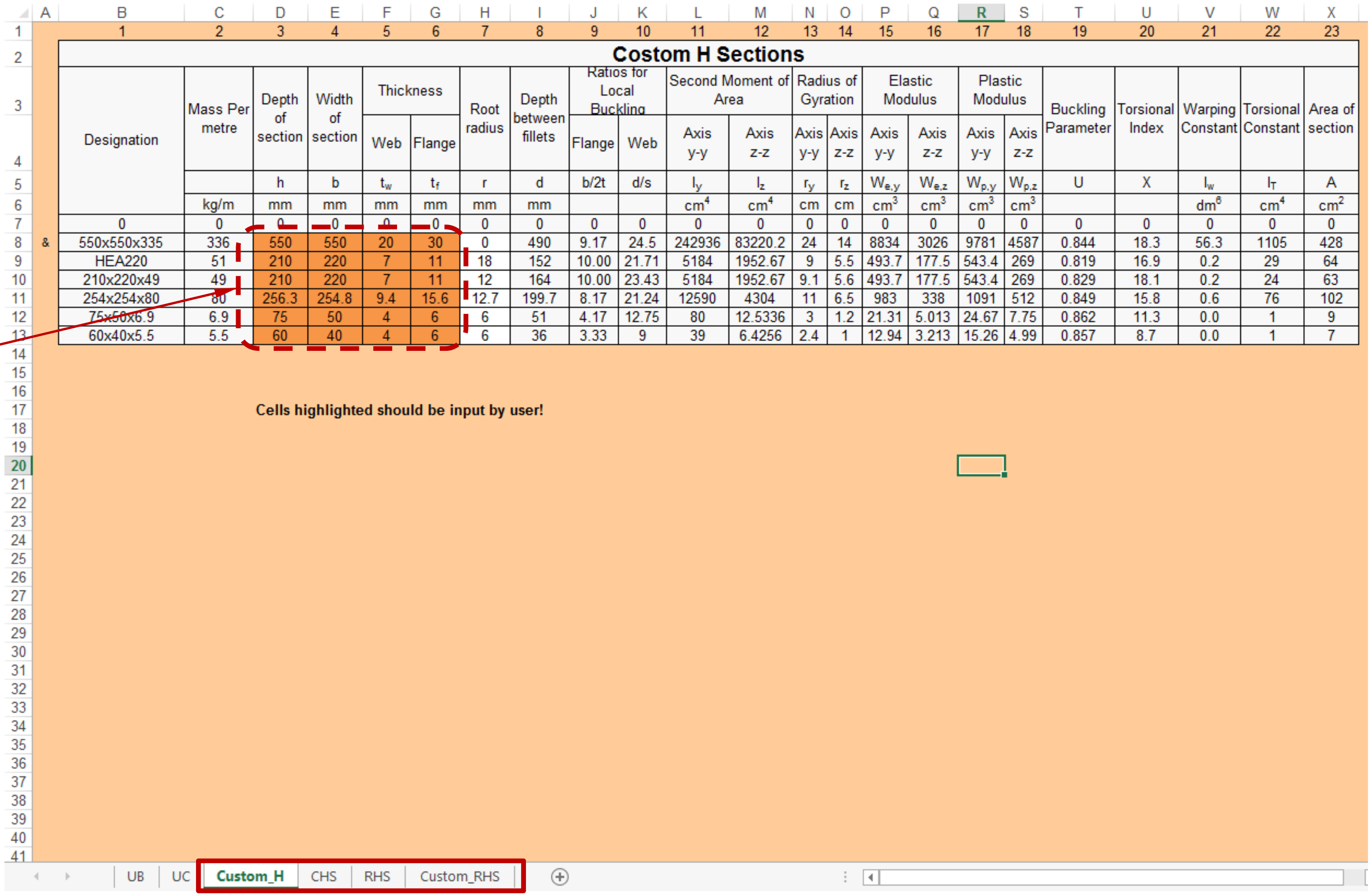
Designation			Mass Per metre	Area of Section	Ratio for Local Buckling	Second Moment of Area	Radius of Gyration	Elastic Modulus	Plastic Modulus	Torsional Constants		Surface Area of Section	Approx Length Per Tonne
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Mark	Outside Diameter	Thickness											
	D	t		A	D/t	I	r	W_e	W_p	I_T	W_t		
	mm	mm	kg/m	cm^2		cm^4	cm	cm^3	cm^3	cm^4	cm^3	m^2/m	m
21.3x3.2	21.3	3.2	1.43	1.82	6.7	0.768	0.65	0.722	1.06	1.54	1.44	0.067	700
26.9x3.2	26.9	3.2	1.87	2.38	8.4	1.7	0.846	1.27	1.81	3.41	2.53	0.085	535
33.7x3	33.7	3	2.27	2.89	11.2	3.44	1.09	2.04	2.84	6.88	4.08	0.106	440
33.7x3.2	33.7	3.2	2.41	3.07	10.5	3.6	1.08	2.14	2.99	7.21	4.28	0.106	415
33.7x3.6	33.7	3.6	2.67	3.4	9.4	3.91	1.07	2.32	3.28	7.82	4.64	0.106	374
33.7x4	33.7	4	2.93	3.73	8.4	4.19	1.06	2.49	3.55	8.38	4.97	0.106	341
42.4x3	42.4	3	2.91	3.71	14.1	7.25	1.4	3.42	4.67	14.5	6.84	0.133	343
42.4x3.2	42.4	3.2	3.09	3.94	13.3	7.62	1.39	3.59	4.93	15.2	7.19	0.133	323
42.4x3.6	42.4	3.6	3.44	4.39	11.8	8.33	1.38	3.93	5.44	16.7	7.86	0.133	290
42.4x4	42.4	4	3.79	4.83	10.6	8.99	1.36	4.24	5.92	18	8.48	0.133	264
48.3x2.5	48.3	2.5	2.82	3.6	19.3	9.46	1.62	3.92	5.25	18.9	7.83	0.152	354
48.3x3	48.3	3	3.35	4.27	16.1	11	1.61	4.55	6.17	22	9.11	0.152	298
48.3x3.2	48.3	3.2	3.56	4.53	15.1	11.6	1.6	4.8	6.52	23.2	9.59	0.152	281
48.3x3.6	48.3	3.6	3.97	5.06	13.4	12.7	1.59	5.26	7.21	25.4	10.5	0.152	252
48.3x4	48.3	4	4.37	5.57	12.1	13.8	1.57	5.7	7.87	27.5	11.4	0.152	229
48.3x5	48.3	5	5.34	6.8	9.7	16.2	1.54	6.69	9.42	32.3	13.4	0.152	187
60.3x2.5	60.3	2.5	3.56	4.54	24.1	19	2.05	6.3	8.36	38	12.6	0.189	281
60.3x3	60.3	3	4.24	5.4	20.1	22.2	2.03	7.37	9.86	44.4	14.7	0.189	236
60.3x3.2	60.3	3.2	4.51	5.74	18.8	23.5	2.02	7.78	10.4	46.9	15.6	0.189	222
60.3x3.6	60.3	3.6	5.03	6.41	16.8	25.9	2.01	8.58	11.6	51.7	17.2	0.189	199
60.3x4	60.3	4	5.55	7.07	15.1	28.2	2	9.34	12.7	56.3	18.7	0.189	180
60.3x5	60.3	5	6.82	8.69	12.1	33.5	1.96	11.1	15.3	67	22.2	0.189	147
76.1x2.5	76.1	2.5	4.54	5.78	30.4	39.2	2.6	10.3	13.5	78.4	20.6	0.239	220
76.1x3	76.1	3	5.41	6.89	25.4	46.1	2.59	12.1	16	92.2	24.2	0.239	185
76.1x3.2	76.1	3.2	5.75	7.33	23.8	48.8	2.58	12.8	17	97.6	25.6	0.239	174
76.1x3.6	76.1	3.6	6.44	8.2	21.1	54	2.57	14.2	18.9	108	28.4	0.239	155
76.1x4	76.1	4	7.11	9.06	19	59.1	2.55	15.5	20.8	118	31	0.239	141
76.1x5	76.1	5	8.77	11.2	15.2	70.9	2.52	18.6	25.3	142	37.3	0.239	114
76.1x6	76.1	6	10.4	13.2	12.7	81.8	2.49	21.5	29.6	164	43	0.239	96.4
76.1x6.3	76.1	6.3	10.8	13.8	12.1	84.8	2.48	22.3	30.8	170	44.6	0.239	92.2
88.9x2.5	88.9	2.5	5.33	6.79	35.6	63.4	3.06	14.3	18.7	127	28.5	0.279	188
88.9x3	88.9	3	6.36	8.1	29.6	74.8	3.04	16.8	22.1	150	33.6	0.279	157
88.9x3.2	88.9	3.2	6.76	8.62	27.8	79.2	3.03	17.8	23.5	158	35.6	0.279	148
88.9x3.6	88.9	3.6	7.57	9.65	24.7	87.9	3.02	19.8	26.2	176	39.5	0.279	132
88.9x4	88.9	4	8.38	10.7	22.2	96.3	3	21.7	28.9	193	43.3	0.279	119
88.9x5	88.9	5	10.3	13.2	17.8	116	2.97	26.2	35.2	233	52.4	0.279	96.7

Hot-finished sections

SS.xls

User Defined Sections

The users only need to input the dimensions of the section, the other sectional properties are automatically calculated!



Costom H Sections

Designation	Mass Per metre	Depth of section	Width of section	Thickness		Root radius	Depth between fillets	Ratios for Local Buckling		Second Moment of Area		Radius of Gyration		Elastic Modulus		Plastic Modulus		Buckling Parameter	Torsional Index	Warping Constant	Torsional Constant	Area of section
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
				Web	Flange			Flange	Web	Axis y-y	Axis z-z	Axis y-y	Axis z-z	Axis y-y	Axis z-z	Axis y-y	Axis z-z					
		h	b	t_w	t_f	r	d	b/2t	d/s	I_y	I_z	r_y	r_z	$W_{e,y}$	$W_{e,z}$	$W_{p,y}$	$W_{p,z}$	U	X	I_w	I_T	A
	kg/m	mm	mm	mm	mm	mm	mm			cm^4	cm^4	cm	cm	cm^3	cm^3	cm^3	cm^3			dm^6	cm^4	cm^2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
550x550x335	336	550	550	20	30	0	490	9.17	24.5	242936	83220.2	24	14	8834	3026	9781	4587	0.844	18.3	56.3	1105	428
HEA220	51	210	220	7	11	18	152	10.00	21.71	5184	1952.67	9	5.5	493.7	177.5	543.4	269	0.819	16.9	0.2	29	64
210x220x49	49	210	220	7	11	12	164	10.00	23.43	5184	1952.67	9.1	5.6	493.7	177.5	543.4	269	0.829	18.1	0.2	24	63
254x254x80	80	256.3	254.8	9.4	15.6	12.7	199.7	8.17	21.24	12590	4304	11	6.5	983	338	1091	512	0.849	15.8	0.6	76	102
75x50x6.9	6.9	75	50	4	6	6	51	4.17	12.75	80	12.5336	3	1.2	21.31	5.013	24.67	7.75	0.862	11.3	0.0	1	9
60x40x5.5	5.5	60	40	4	6	6	36	3.33	9	39	6.4256	2.4	1	12.94	3.213	15.26	4.99	0.857	8.7	0.0	1	7

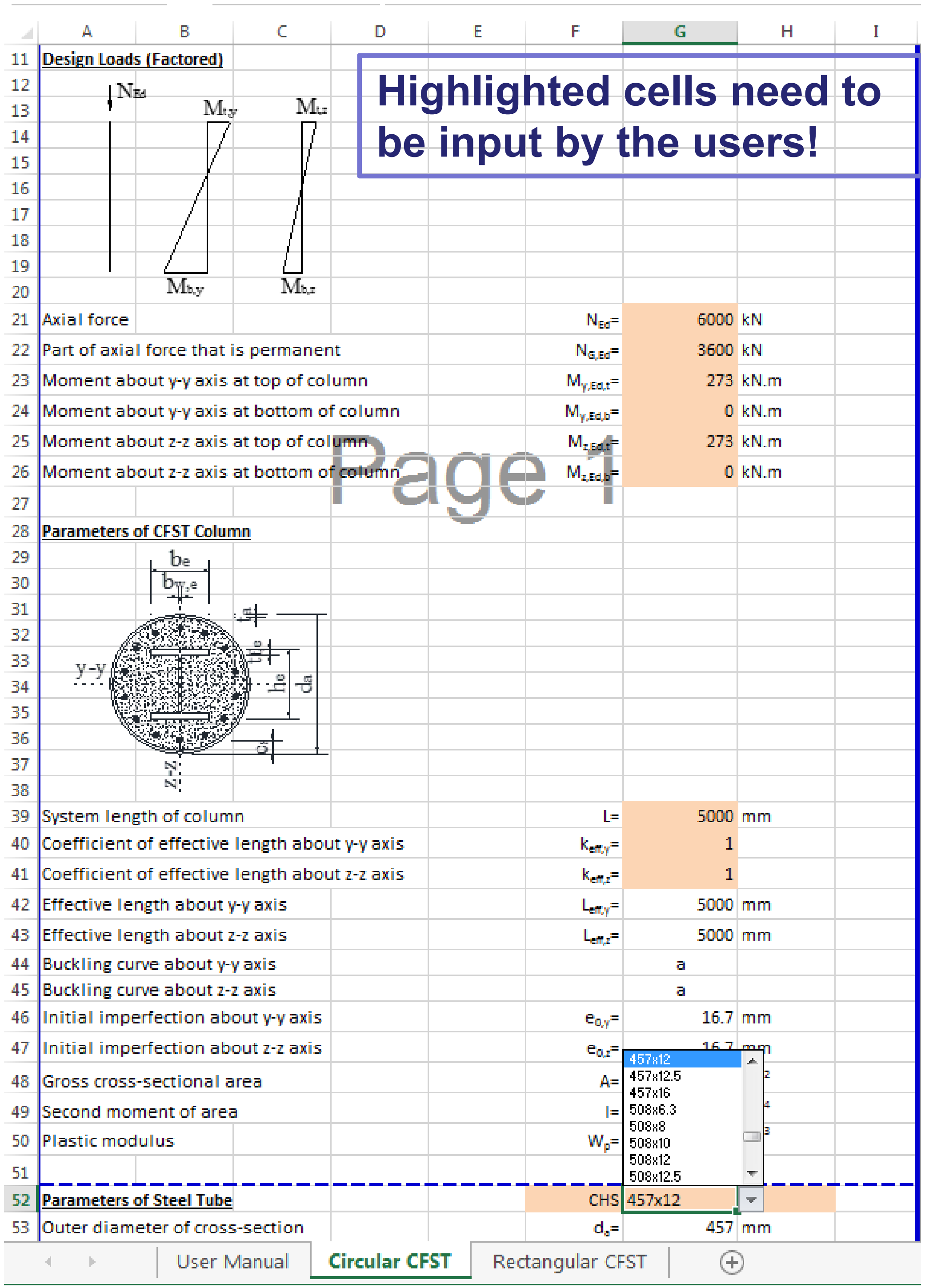
Cells highlighted should be input by user!

User-defined sections

CFST Design.xlsx

Main Program

- Input data
  - Design Loads
  - Section Sizes
  - Material Properties

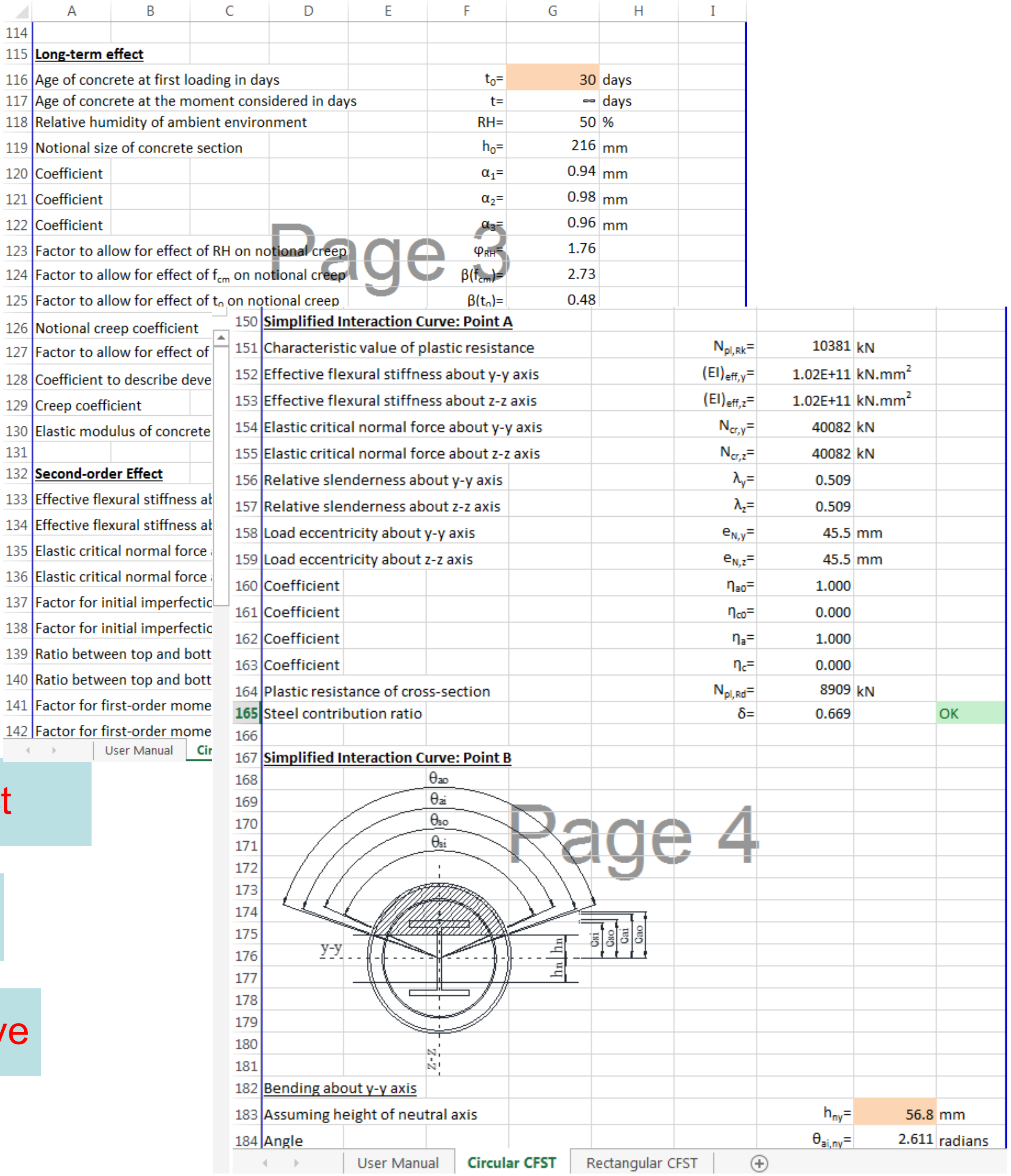


11	Design Loads (Factored)			
21	Axial force	N_{Ed}=	6000	kN
22	Part of axial force that is permanent	$N_{G,Ed}$=	3600	kN
23	Moment about y-y axis at top of column	$M_{y,Ed,t}$=	273	kN.m
24	Moment about y-y axis at bottom of column	$M_{y,Ed,b}$=	0	kN.m
25	Moment about z-z axis at top of column	$M_{z,Ed,t}$=	273	kN.m
26	Moment about z-z axis at bottom of column	$M_{z,Ed,b}$=	0	kN.m
28	Parameters of CFST Column			
39	System length of column	L=	5000	mm
40	Coefficient of effective length about y-y axis	$k_{eff,y}$=	1	
41	Coefficient of effective length about z-z axis	$k_{eff,z}$=	1	
42	Effective length about y-y axis	$L_{eff,y}$=	5000	mm
43	Effective length about z-z axis	$L_{eff,z}$=	5000	mm
44	Buckling curve about y-y axis		a	
45	Buckling curve about z-z axis		a	
46	Initial imperfection about y-y axis	$e_{0,y}$=	16.7	mm
47	Initial imperfection about z-z axis	$e_{0,z}$=	16.7	mm
48	Gross cross-sectional area	A=		
49	Second moment of area	I=		
50	Plastic modulus	W_p=		
52	Parameters of Steel Tube	CHS	457x12	
53	Outer diameter of cross-section	d_a=	457	mm

457x12
457x12.5
457x16
508x6.3
508x8
508x10
508x12
508x12.5

CFST Design.xlsx

Main Program



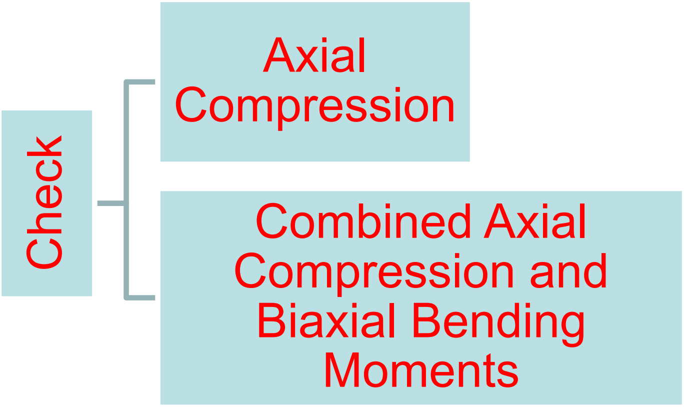
	A	F	G	H
114				
115	**Long-term effect**			
116	Age of concrete at first loading in days	t_0=	30	days
117	Age of concrete at the moment considered in days	t=	∞	days
118	Relative humidity of ambient environment	RH=	50	%
119	Notional size of concrete section	h_0=	216	mm
120	Coefficient	α_1=	0.94	mm
121	Coefficient	α_2=	0.98	mm
122	Coefficient	α_3=	0.96	mm
123	Factor to allow for effect of RH on notional creep	φ_{RH}=	1.76	
124	Factor to allow for effect of f_{cm} on notional creep	$\beta(f_{cm})$=	2.73	
125	Factor to allow for effect of t_0 on notional creep	$\beta(t_0)$=	0.48	
126	Notional creep coefficient			
127	Factor to allow for effect of			
128	Coefficient to describe deve			
129	Creep coefficient			
130	Elastic modulus of concrete			
131				
132	**Second-order Effect**			
133	Effective flexural stiffness al			
134	Effective flexural stiffness al			
135	Elastic critical normal force			
136	Elastic critical normal force			
137	Factor for initial imperfectic			
138	Factor for initial imperfectic			
139	Ratio between top and bott			
140	Ratio between top and bott			
141	Factor for first-order mome			
142	Factor for first-order mome			

150	**Simplified Interaction Curve: Point A**				
151	Characteristic value of plastic resistance	$N_{pl,Rk}$=	10381	kN	
152	Effective flexural stiffness about y-y axis	$(EI)_{eff,y}$=	1.02E+11	kN.mm^2	
153	Effective flexural stiffness about z-z axis	$(EI)_{eff,z}$=	1.02E+11	kN.mm^2	
154	Elastic critical normal force about y-y axis	$N_{cr,y}$=	40082	kN	
155	Elastic critical normal force about z-z axis	$N_{cr,z}$=	40082	kN	
156	Relative slenderness about y-y axis	λ_y=	0.509		
157	Relative slenderness about z-z axis	λ_z=	0.509		
158	Load eccentricity about y-y axis	$e_{N,y}$=	45.5	mm	
159	Load eccentricity about z-z axis	$e_{N,z}$=	45.5	mm	
160	Coefficient	η_{a0}=	1.000		
161	Coefficient	η_{c0}=	0.000		
162	Coefficient	η_a=	1.000		
163	Coefficient	η_c=	0.000		
164	Plastic resistance of cross-section	$N_{pl,Rd}$=	8909	kN	
165	Steel contribution ratio	δ=	0.669		OK
166					
167	**Simplified Interaction Curve: Point B**				
168–181					
182	Bending about y-y axis				
183	Assuming height of neutral axis	h_{ny}=	56.8	mm	
184	Angle	$\theta_{ai,ny}$=	2.611	radians	

Calculation
- Long-Term Effect
- Second-Order Effect
- M-N Interaction Curve

CFST Design.xlsx

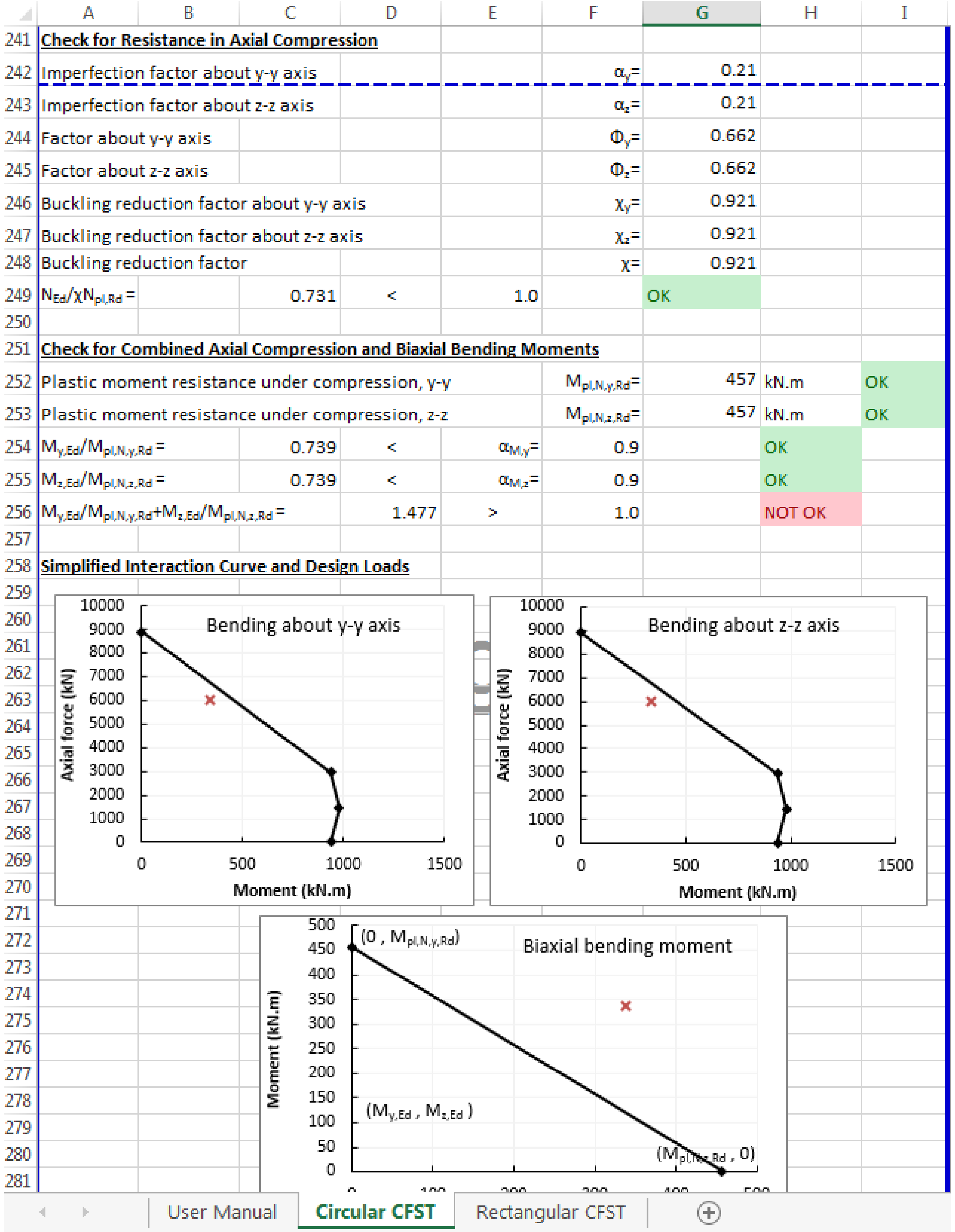
Main Program



Check

Axial Compression

Combined Axial Compression and Biaxial Bending Moments



	A	B	C	D	E	F	G	H	I
241	**Check for Resistance in Axial Compression**								
242	Imperfection factor about y-y axis					α_y=	0.21		
243	Imperfection factor about z-z axis					α_z=	0.21		
244	Factor about y-y axis					Φ_y=	0.662		
245	Factor about z-z axis					Φ_z=	0.662		
246	Buckling reduction factor about y-y axis					χ_y=	0.921		
247	Buckling reduction factor about z-z axis					χ_z=	0.921		
248	Buckling reduction factor					χ=	0.921		
249	$N_{Ed}/\chi N_{pl,Rd}$ =		0.731	<	1.0		OK		
250									
251	**Check for Combined Axial Compression and Biaxial Bending Moments**								
252	Plastic moment resistance under compression, y-y					$M_{pl,N,y,Rd}$=	457	kN.m	OK
253	Plastic moment resistance under compression, z-z					$M_{pl,N,z,Rd}$=	457	kN.m	OK
254	$M_{y,Ed}/M_{pl,N,y,Rd}$ =		0.739	<	$\alpha_{M,y}$=	0.9		OK	
255	$M_{z,Ed}/M_{pl,N,z,Rd}$ =		0.739	<	$\alpha_{M,z}$=	0.9		OK	
256	$M_{y,Ed}/M_{pl,N,y,Rd}+M_{z,Ed}/M_{pl,N,z,Rd}$ =			1.477	>	1.0		NOT OK	
257									
258	**Simplified Interaction Curve and Design Loads**								
259									
260									
261									
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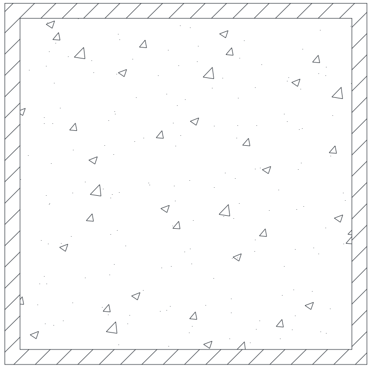
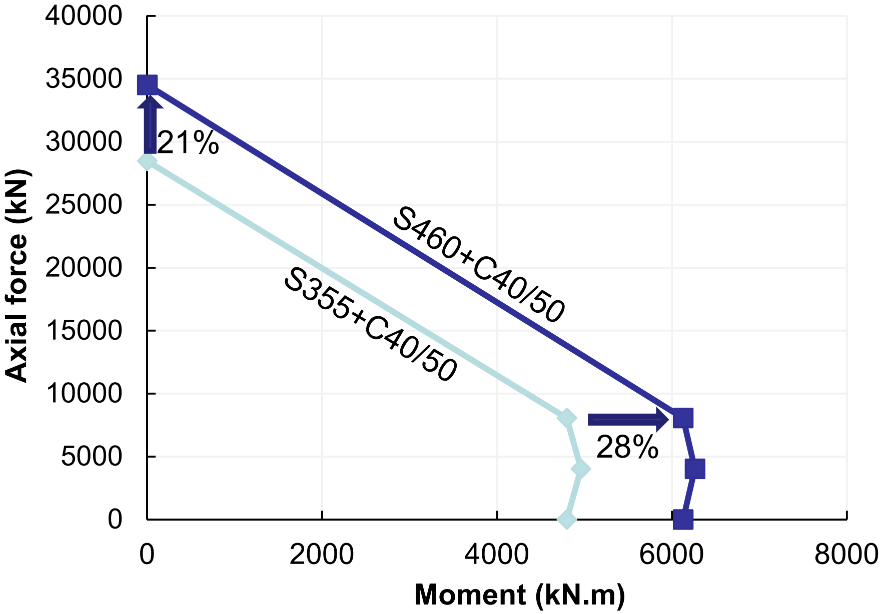
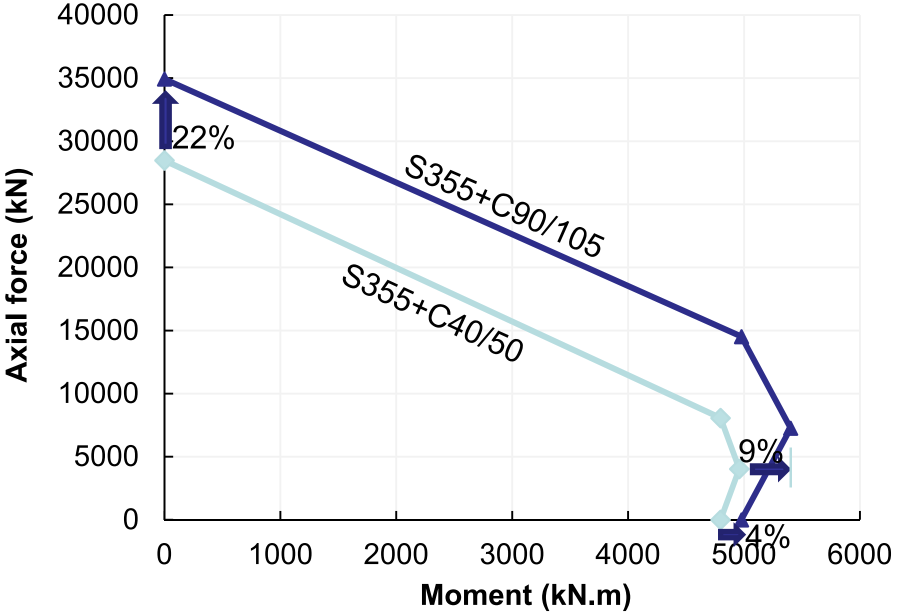
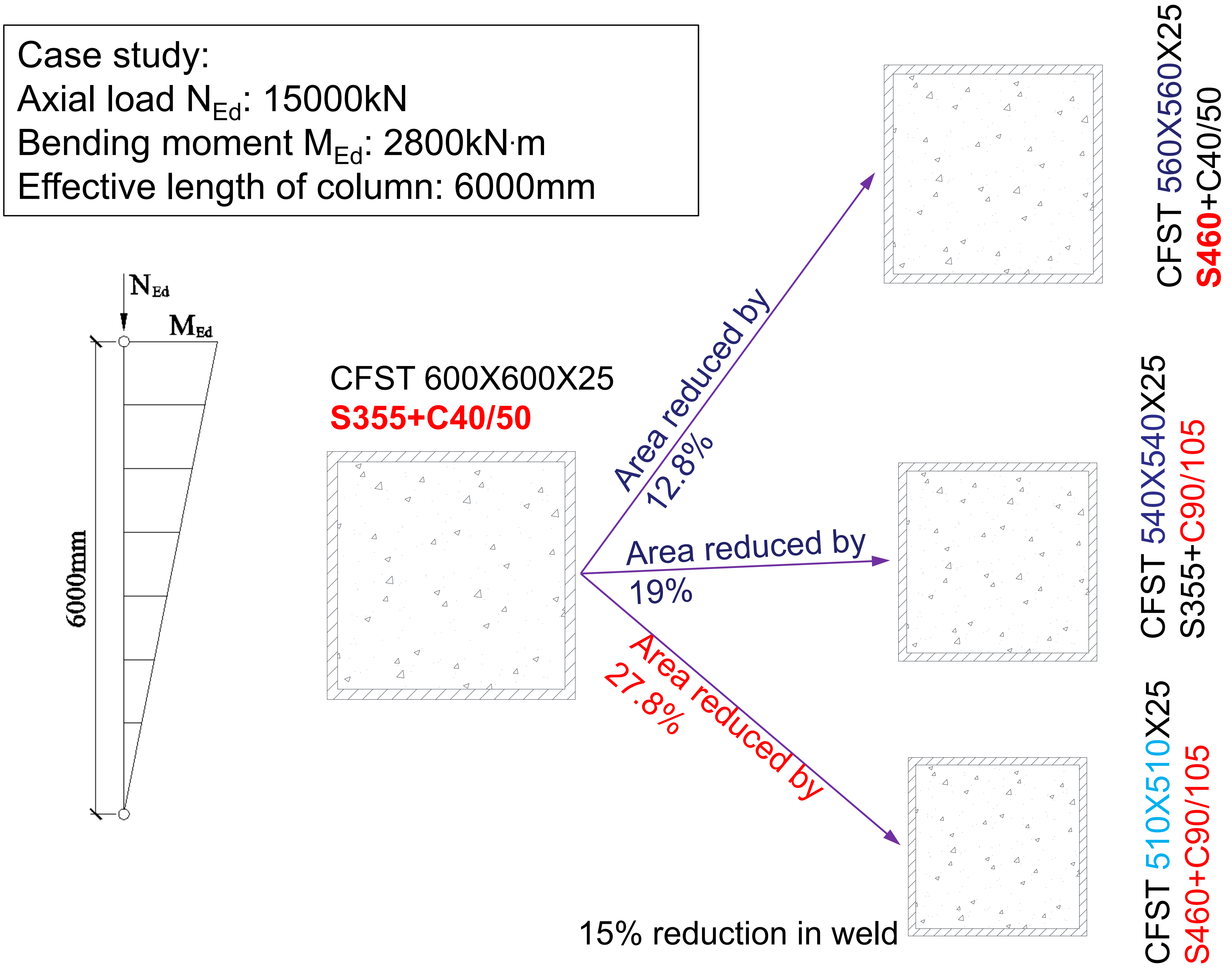
CFST 600X600X25





- Significantly increase axial compression resistance;
- Bending resistance benefits more from the increase of steel strength;
- No re-bars work.





Case study:
Axial load N_{Ed}: 15000kN
Bending moment M_{Ed}: 2800kN·m
Effective length of column: 6000mm

CFST 600X600X25
S355+C40/50

Area reduced by 12.8%

Area reduced by 19%

Area reduced by 27.8%

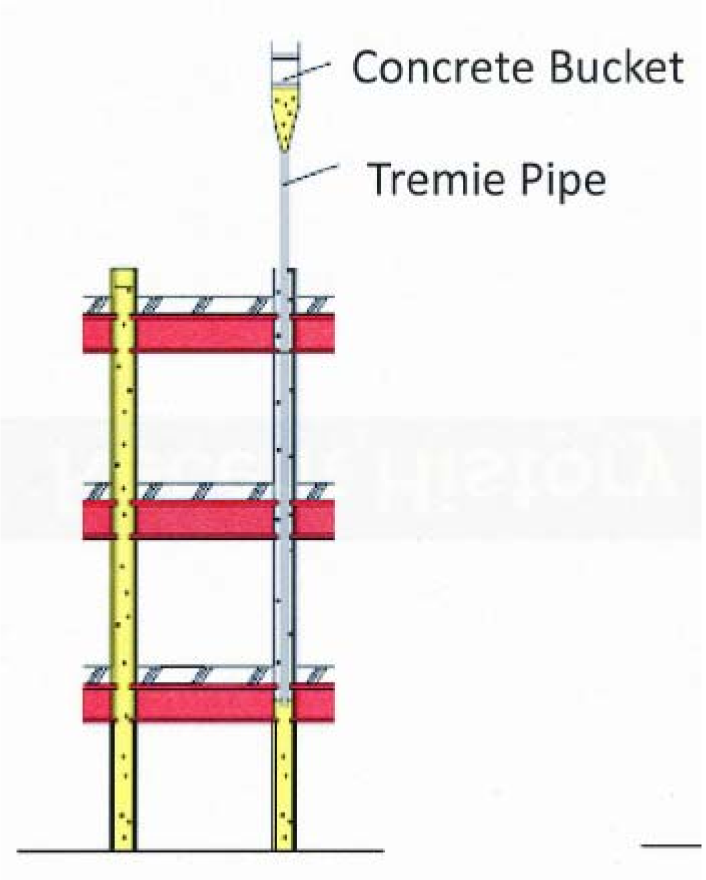
CFST 560X560X25
S460+C40/50

CFST 540X540X25
S355+C90/105

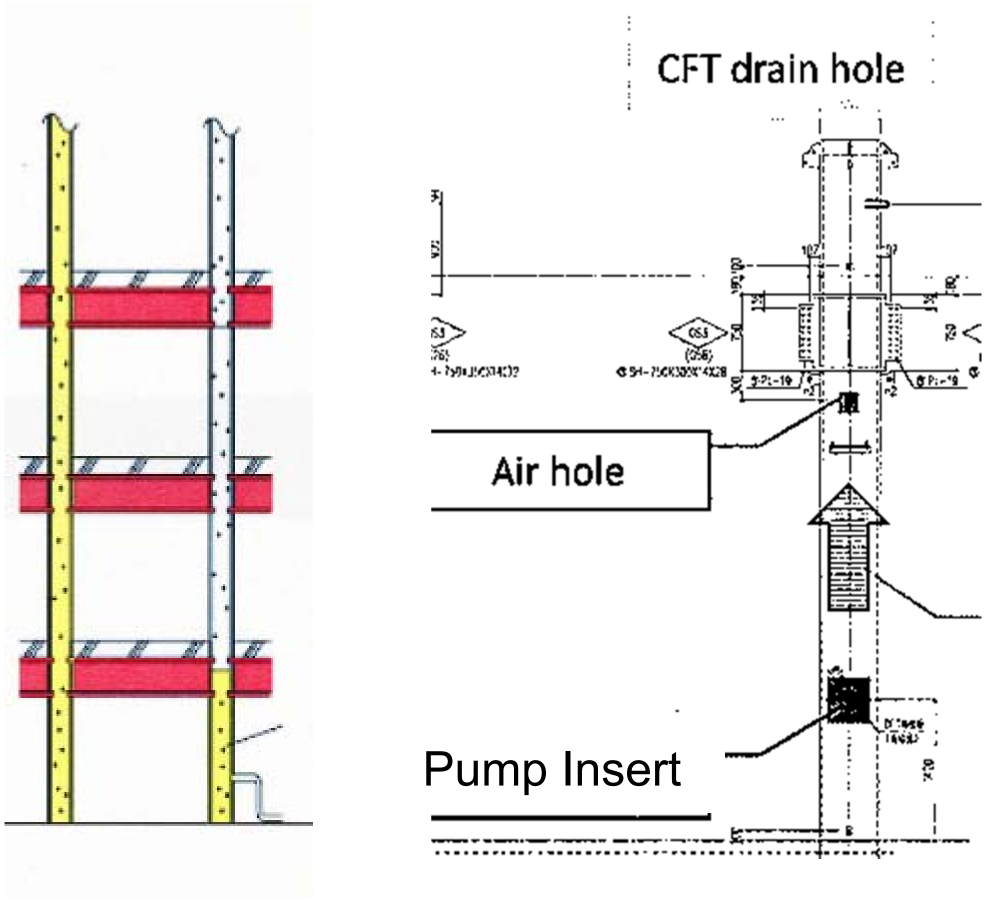
CFST 510X510X25
S460+C90/105

15% reduction in weld

How to Fill Concrete in Steel Tube?



Cast in method

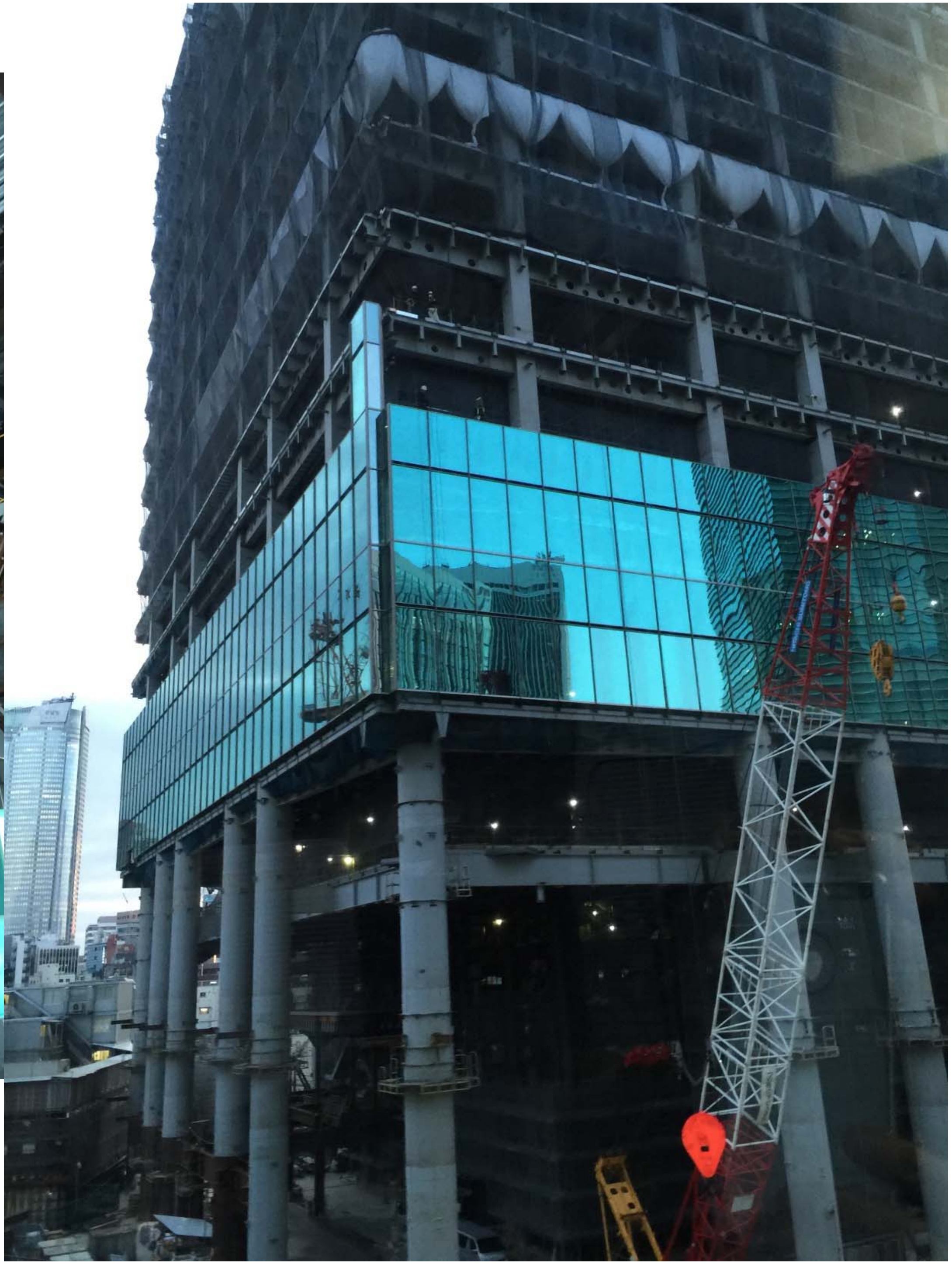


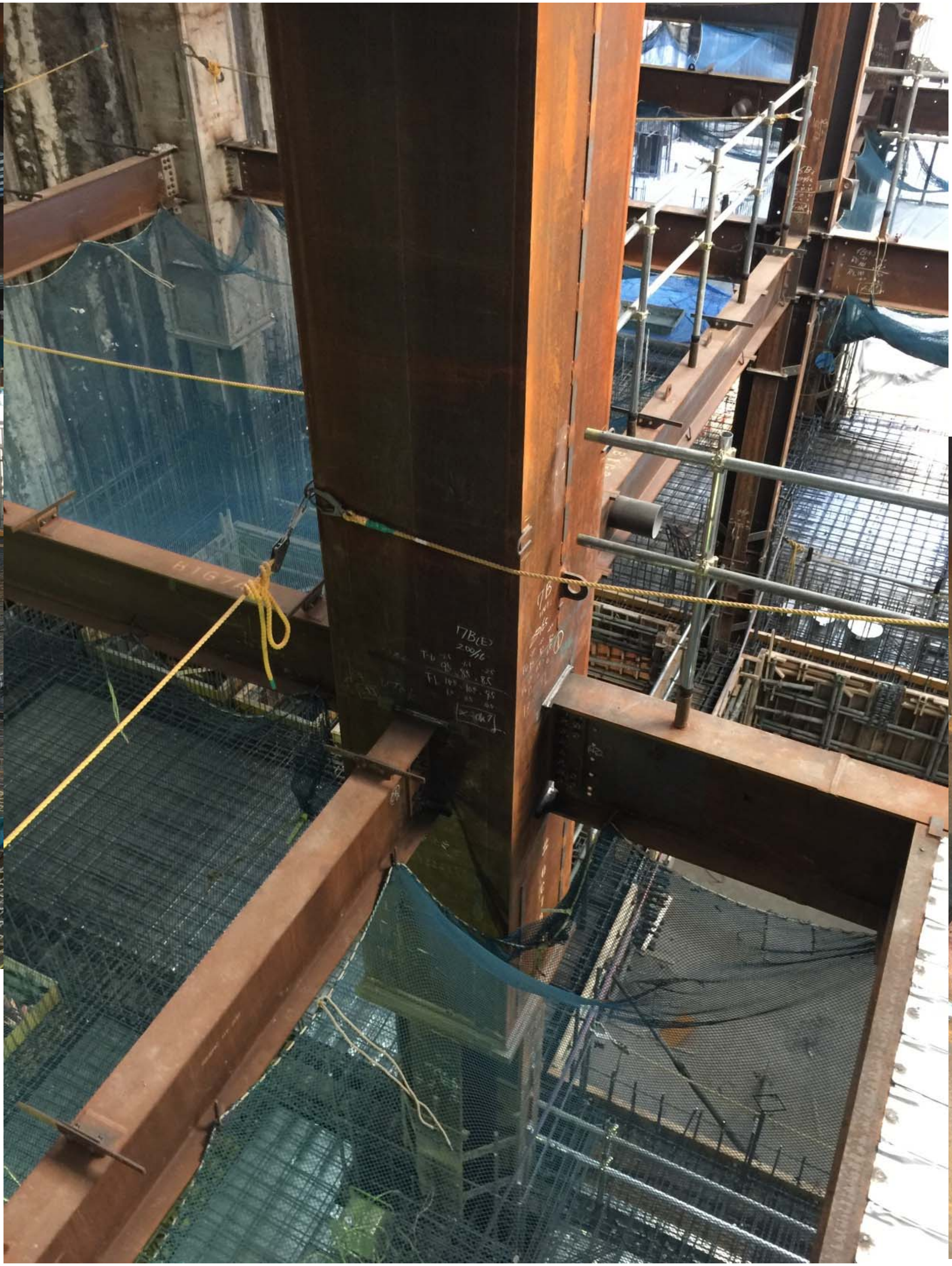
Pump from below

Cast In Method

Pump from below

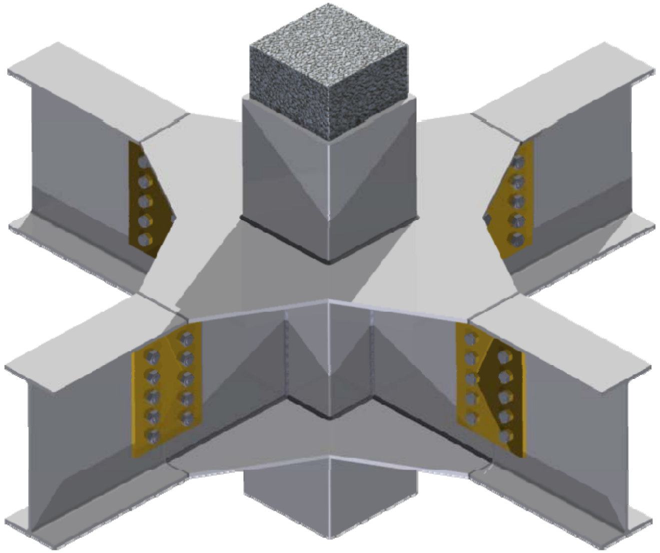
Concrete Insert Hole

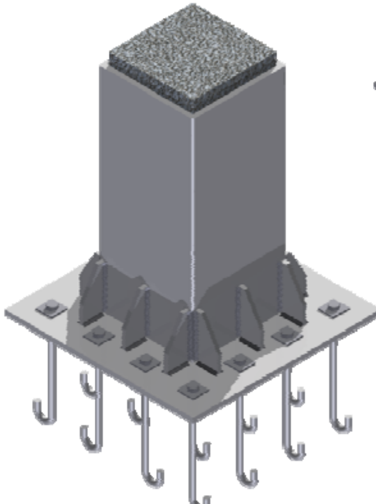


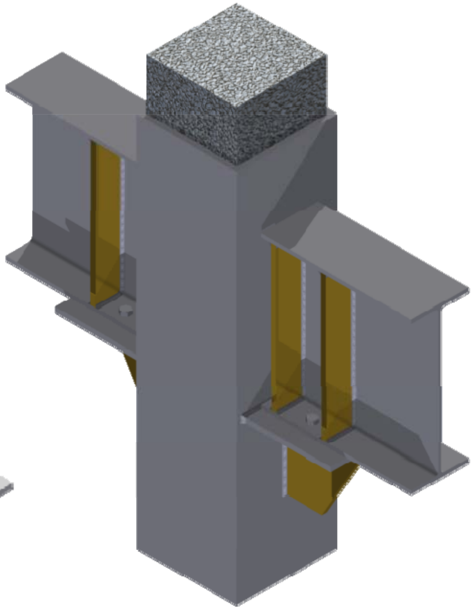

17B(E)

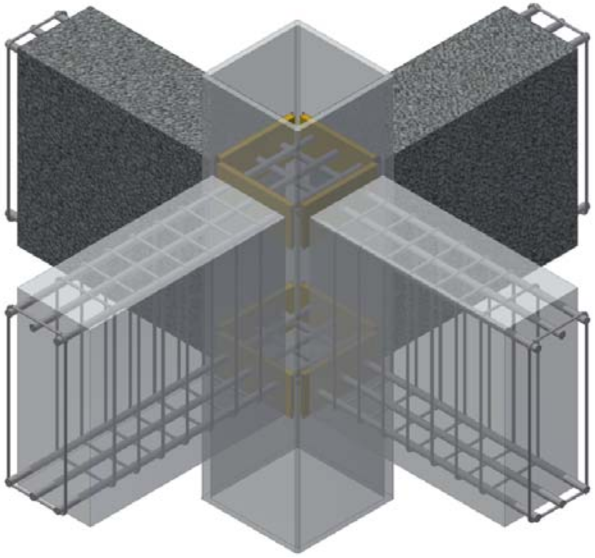
Design Guide

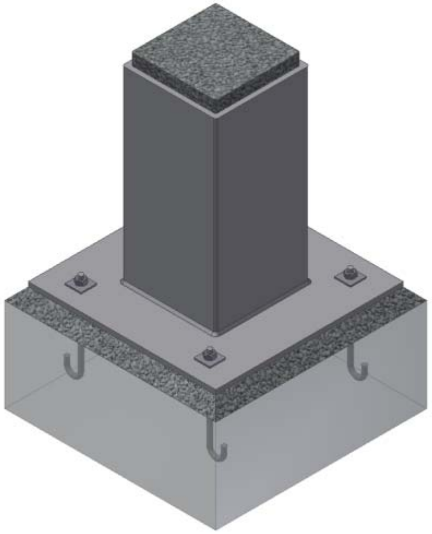
Connection Design

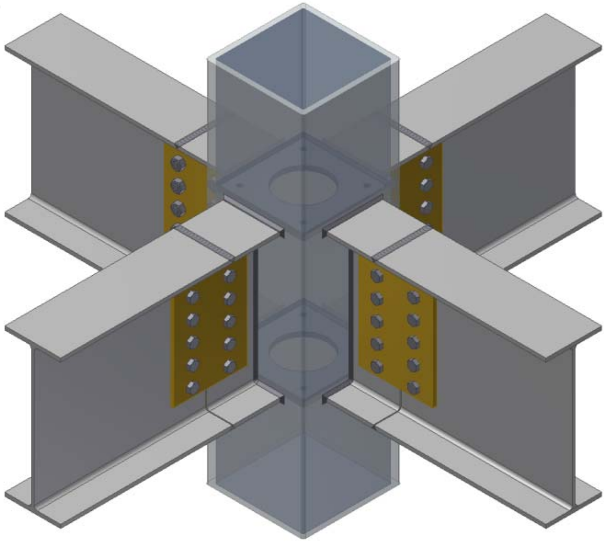












Conclusions

- CFT columns have higher structural resistance compared to steel and RC columns
- They require less fire protection
- They facilitate long span floor layout offering flexible architectural planning
- Smaller column size for high rise construction
- Use of higher strength steel and high strength concrete requires less site work, less welding and higher productivity
- New design guide can be used to design CFT columns more economically and safely