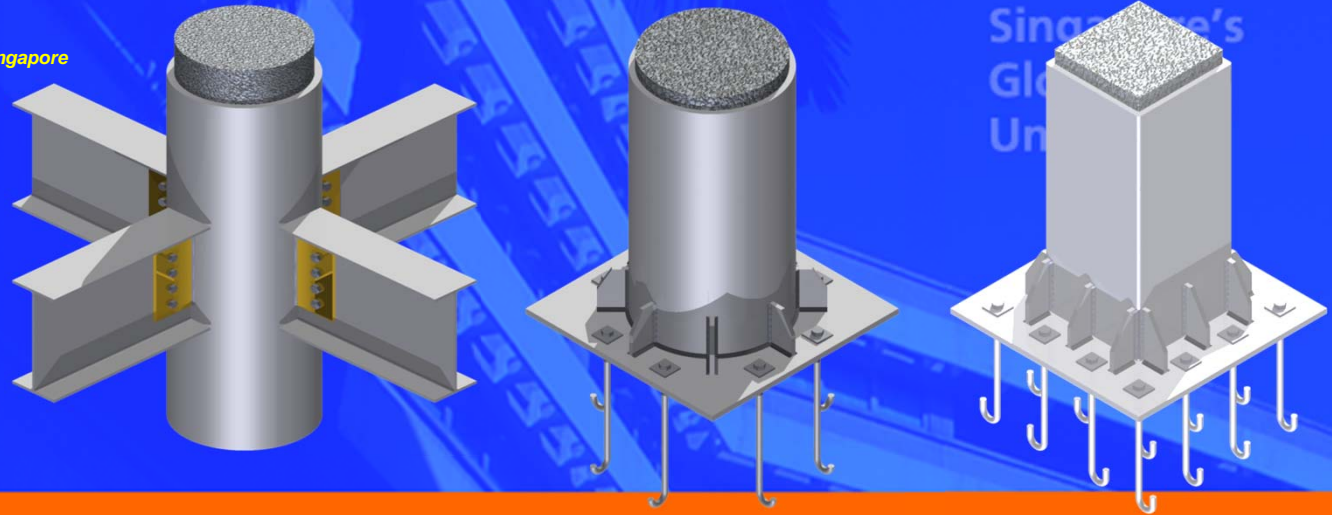


International Symposium on Design and Construction of Steel and Composite Structures, 2015

22 January 2015

LT7A, 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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National University of Singapore



## Tall buildings using high strength concrete

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



International Commerce 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 <sup>2</sup> )	Steel ( $f_y$ , N/mm <sup>2</sup> )	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



**Recent High-rise Buildings**



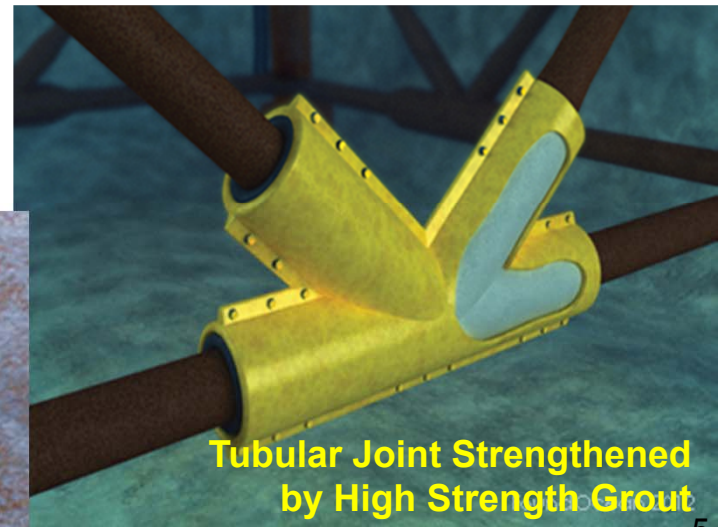
**Bridges**



**Ships**



**Offshore**



**Tubular Joint Strengthened  
by High Strength Grout**

## Material strengths allowed in modern design codes

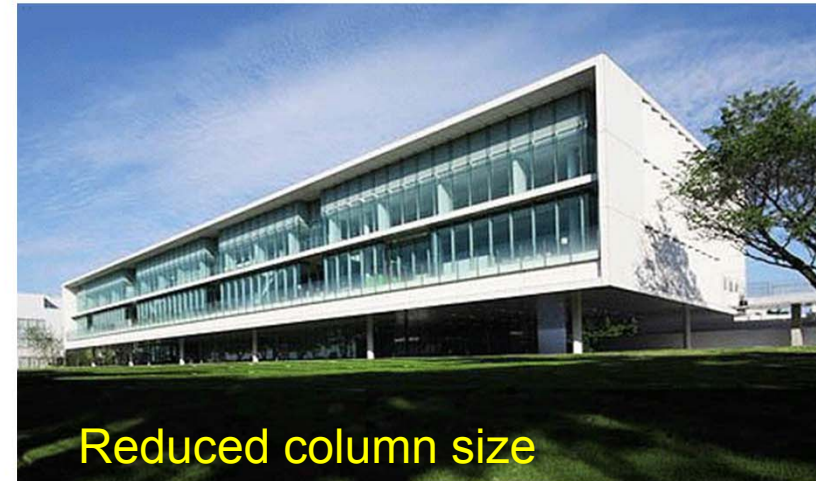
Codes	Steel yield strength (N/mm <sup>2</sup> )	Concrete cylinder strength, (N/mm <sup>2</sup> )
USA: AISC 360-10	≤ 525	21 ~ 70
China: DBJ/T13-51-2010	235 ~ 430	25 ~ 65
Japan: AIJ	235 ~ 440	18 ~ 90
EN 1992	-	Up to 90
EN 1993 1-1 & 1-12	235 ~ 700	-
EN 1994	235 ~ 460	20 ~ 50

Eurocode 4 should be extended to cater for higher strength concretes and steels since the 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)

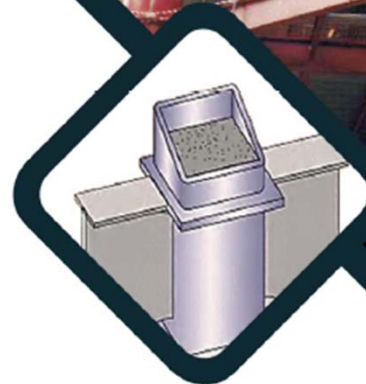
1. Concrete filled steel tubes (**steel: 780MPa, concrete: 160MPa**) for the main columns; column size reduced from **800mm** (based normal strength materials) to **500mm**.
2. Ultra high strength fire-reinforced mortar (**170MPa**) is used for indoor bridges. The depth of the bridge is kept to 335mm.



# DESIGN GUIDE FOR CONCRETE FILLED TUBULAR MEMBERS WITH HIGH STRENGTH MATERIALS

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

J Y Richard Liew  
M X Xiong



Building and Construction Authority



## Launching of New Design Guide (2015) For Singapore

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

# **Member of the Local Expert Committee**

**Chairman: Prof Richard Liew National University of Singapore**

**A/Prof. Sing Ping Chiew, Nanyang Technological University**

**Mr. Thanabal Kaliannan, Singapore Structural Steel Society**

**A/Prof. Sze Dai Pang, National University of Singapore**

**Dr. Chi Trung Tran, Building and Construction Authority**

**Dr. Tongyun Wang, National University of Singapore**

**Dr. Dexin Xiong, National University of Singapore**

# Members of the International Expert Committee for the Design Guide

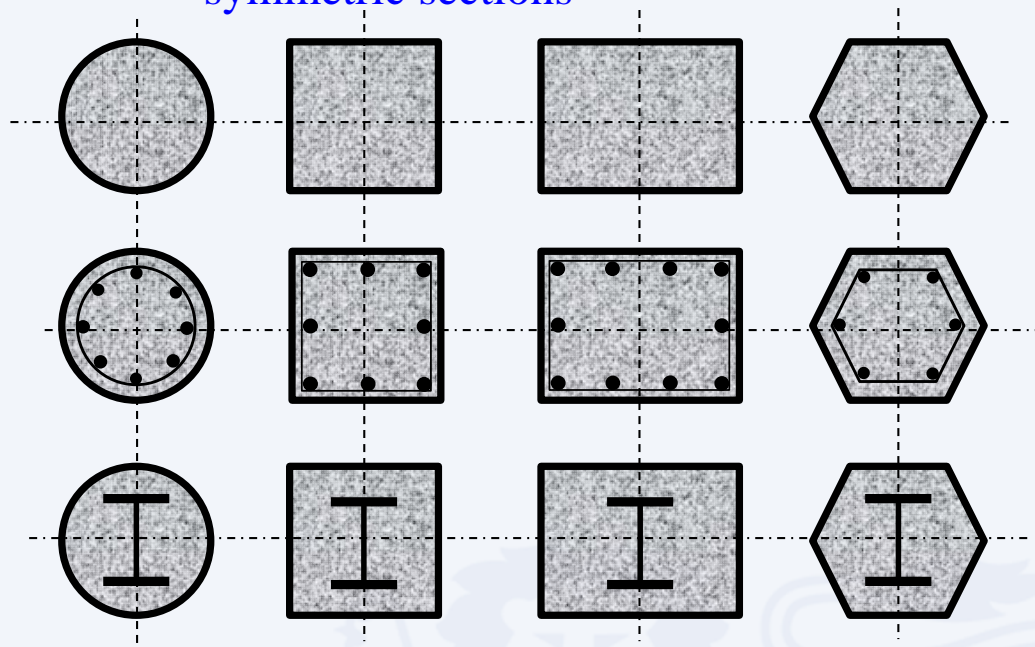
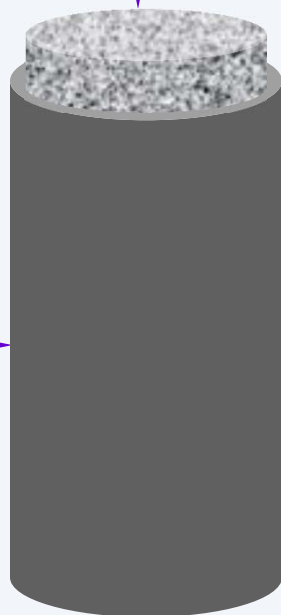
- Professor Reidar Bjorhovde, The Bjorhovde Group, **USA**
- Professor Siu Lai Chan, Hong Kong Polytechnic University, **Hong Kong**
- Professor Lin Hai Han, Tsinghua University, **Beijing China**
- Professor Akihiko Kawano, Kyushu University, **Japan**
- Professor Dennis Lam, University of Bradford, **UK**
- Professor Guo Qiang Li, Tongji University, **Shanghai China**
- Mr. Takayuki Nanba, JFE Steel Corporation, **Japan**
- Professor David A Nethercot, Imperial College London, **UK**
- Professor Keigo Tsuda, University of Kitakyushu, **Japan**
- Professor Brian Uy, University of New South Wales, **Australia**
- Professor Yong Wang, The University of Manchester, **UK**
- Professor Ben Young, The University of Hong Kong, **Hong Kong**

Concrete core  
(up to C90)

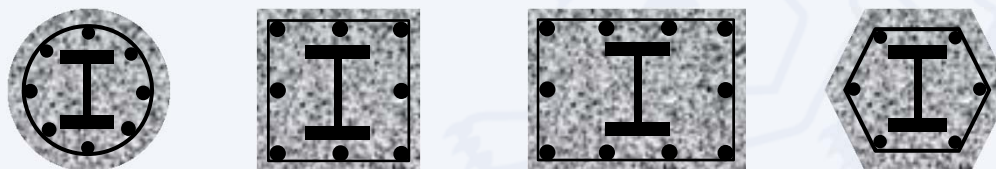
Types of CFST columns with double symmetric sections

Steel tube  
(up to S550)

CFST Column



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



## Database on CFST column tests

### 1) Database by C. Douglas Goode, University of Manchester

1819 test data collected until 2007

### 2) Database extended by Richard Liew, National University of Singapore

\* **2033 test data** collected until 2014

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 sections, as stipulated in EN 1994-1-1, are excluded;

\* Concrete compressive cylinder strength:  $8.5\text{N/mm}^2 \sim 243\text{N/mm}^2$ ;

\* Steel yield strength:  $178\text{N/mm}^2 \sim 853\text{N/mm}^2$ ;

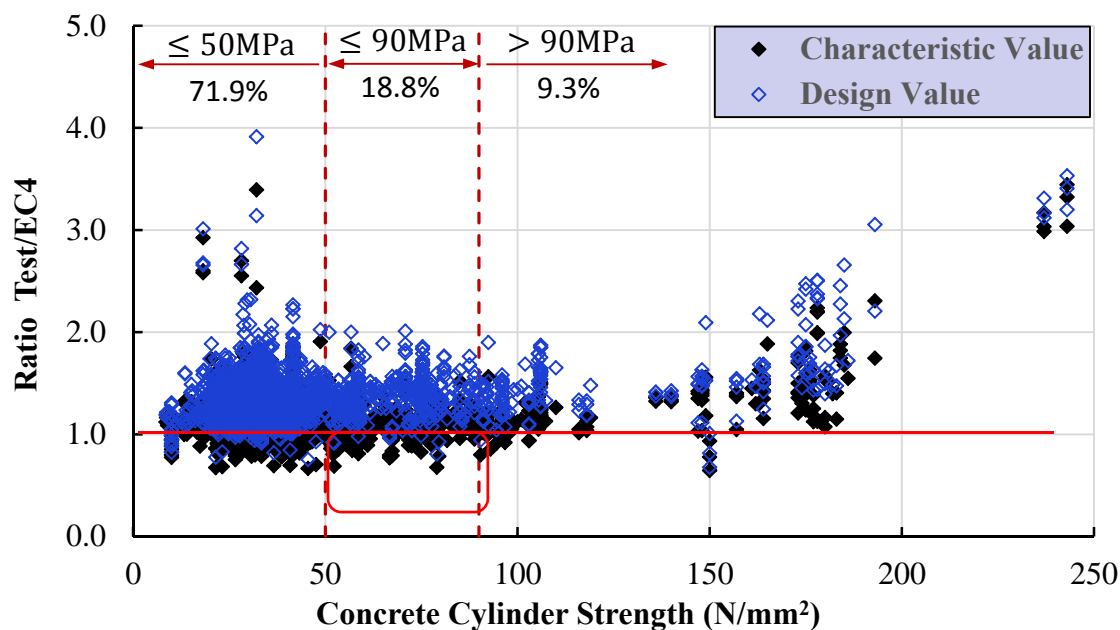
Member height to section smaller dimension ratio:  $0.67 \sim 60$ ;

Relative slenderness  $\bar{\lambda}$  :  $0.02 \sim 1.30$ .

# Influence of concrete strength

Type of column		Compressive cylinder strength of concrete		
		≤50 N/mm <sup>2</sup>	51 to 90 N/mm <sup>2</sup>	>90 N/mm <sup>2</sup>
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  $\eta$  for concrete;  
 {value4} = design strengths with reduction factor  $\eta$  for concrete.



## Extension of EC4 using high strength concrete

For high strength concrete with  $f_{ck} > 50\text{N/mm}^2$ , 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/mm <sup>2</sup> )	54	57	63	68	72
% Reduction	2.5%	5.0%	10.0%	15.0%	20.0%

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

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

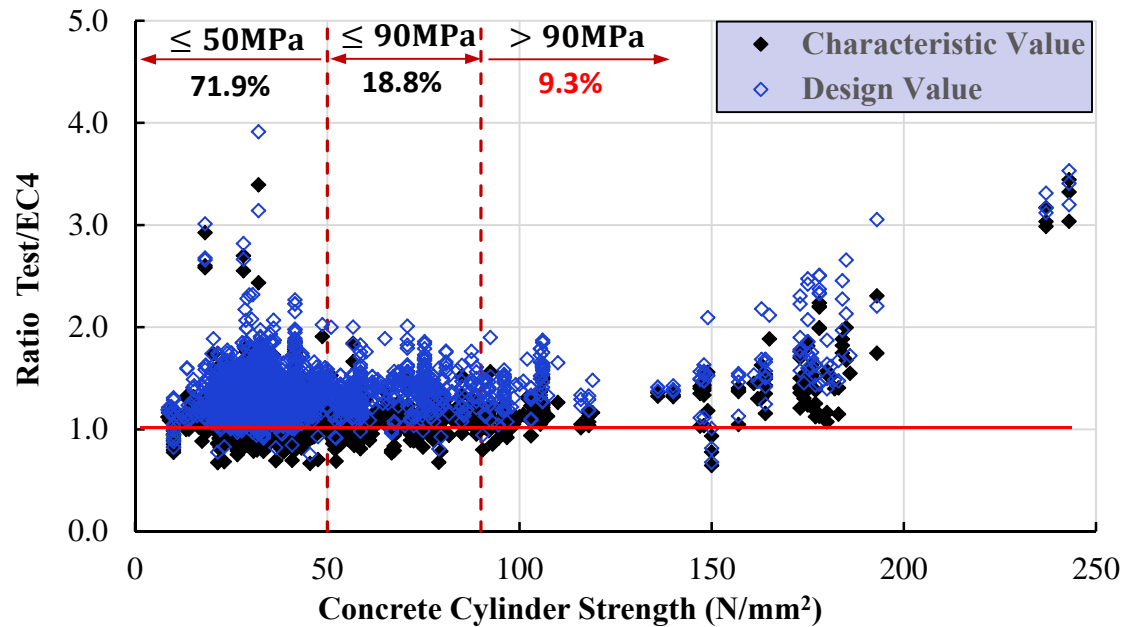
Strength classes	C55/67	C60/75	C70/85	C80/95	C90/105
Modified secant modulus (GPa)	38.0	38.6	39.6	40.4	41.1
% Reduction	0.7%	1.3%	2.8%	4.3%	5.9%

# Design of CFSTs

## High Strength Concrete with Reduction Factor

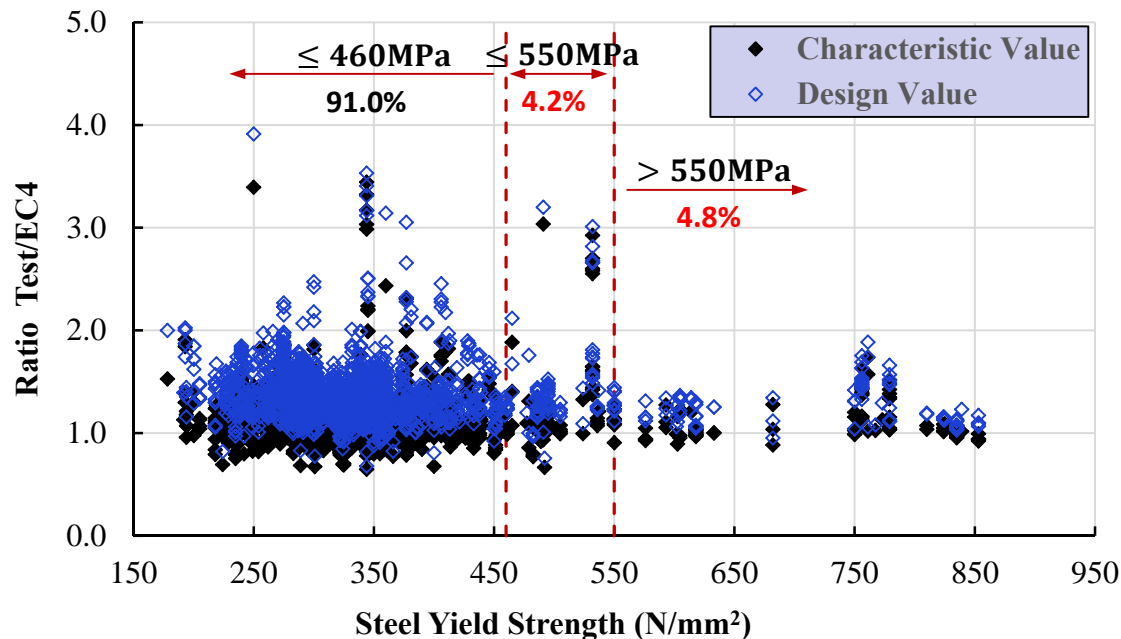
Type of column		Compressive cylinder strength of concrete		
		$\leq 50 \text{ N/mm}^2$	51 to 90 $\text{N/mm}^2$	$> 90 \text{ N/mm}^2$
All test data	Nos.	1461	382	190
	Test/EC4 $\geq 1$	77.3% (98.3%)	[78.3%] {97.6%}	[93.2%] {98.4%}
	Av.	1.133 (1.339)	[1.094] {1.361}	[1.345] {1.597}
	St. Dev.	0.210 (0.240)	[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  $\eta$  for concrete;  
 {value4} based on design strengths with reduction factor  $\eta$  for concrete.

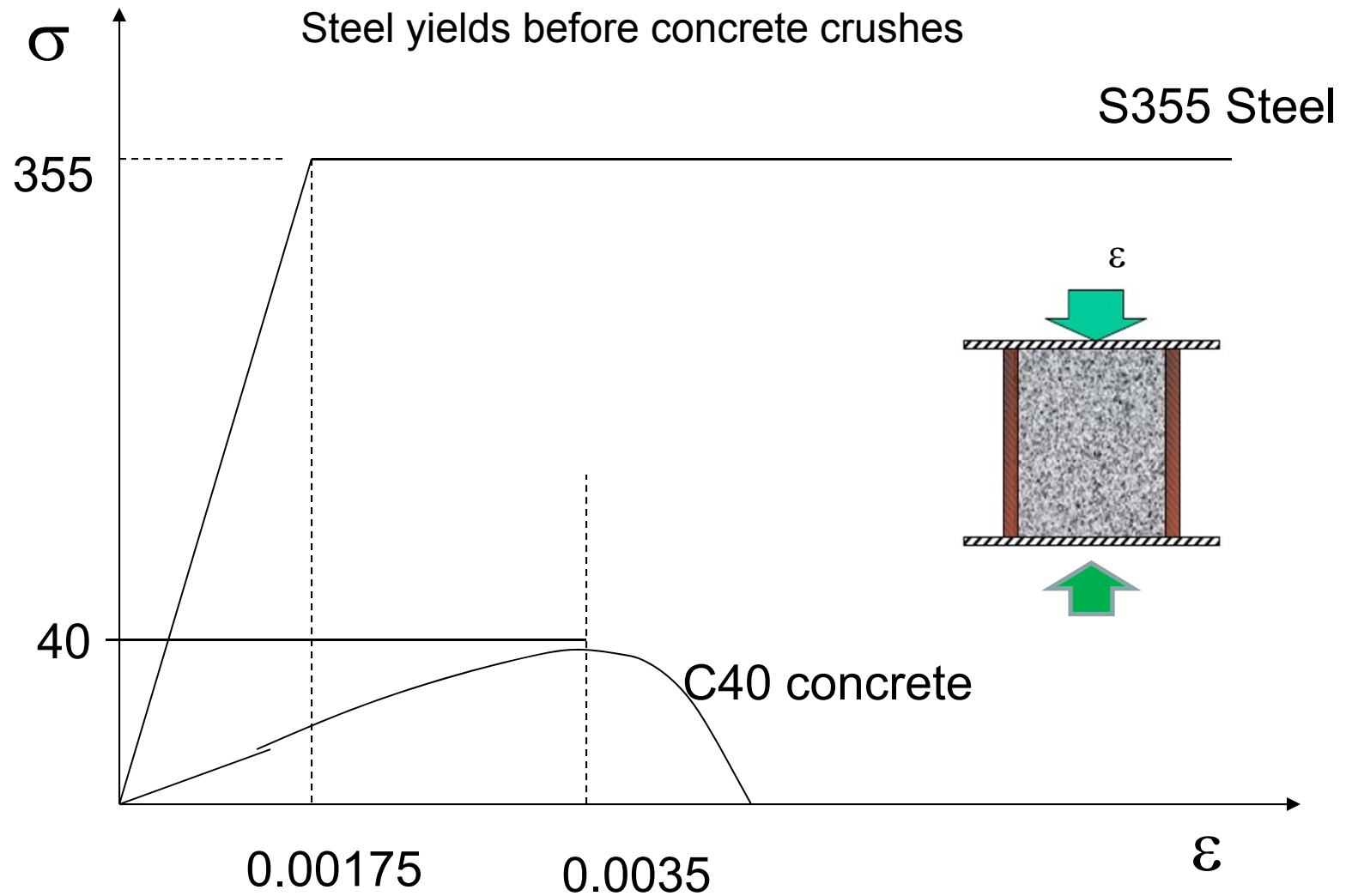


# Influence of steel strength of Test/EC4 Ratio

Types of column		Yield strength of steel		
		$\leq 460\text{N/mm}^2$	$\leq 550\text{N/mm}^2$	$> 550\text{N/mm}^2$
<b>All test data</b>	<b>Nos.</b>	<b>1850</b>	<b>86</b>	<b>97</b>
	<b>Test/EC4 <math>\geq 1</math></b>	<b>79.0% (98.3%)</b>	<b>84.9% (95.3%)</b>	<b>73.2% (99.0%)</b>
	<b>Av.</b>	<b>1.142 (1.370)</b>	<b>1.256 (1.435)</b>	<b>1.114 (1.244)</b>
	<b>St. Dev.</b>	<b>0.225 (0.262)</b>	<b>0.455 (0.440)</b>	<b>0.179 (0.197)</b>



# Compatibility of Materials for Concrete Filled Tubes



## 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.

# Summary on Design Guide

- 1) Current EC4 method can be extended to the design of CFST columns with steel strength up to  $550\text{N/mm}^2$  and concrete compressive cylinder strength up to  $90\text{N/mm}^2$ , with the following modifications:
  - **Class 4 section should not be used to avoid local buckling of steel tube.**
  - **Matching grades of steel and concrete materials must be observed.**
  - **Strength reduction factor to be applied on high strength concrete and the secant modulus of concrete should be modified accordingly**
  
- 2) Although this design guide may be applied to CFST columns with compressive cylinder strength **higher than  $90\text{N/mm}^2$** , more tests are needed to justify its use. It is proposed to use 80% strength of ultra-high strength cement composite grout and ignore the core confinement effect in the design of CFSTs.

# Ultra High Performance Cement Composite (UHPC) with compressive strength 150-200MPa developed in NUS

## Ultra High Performance Concrete (UHPC)

**High strength of 150- 200MPa**

**Ductility – bend like a metal**

**Good workability – self compacting**

**Durability – extremely low permeability**

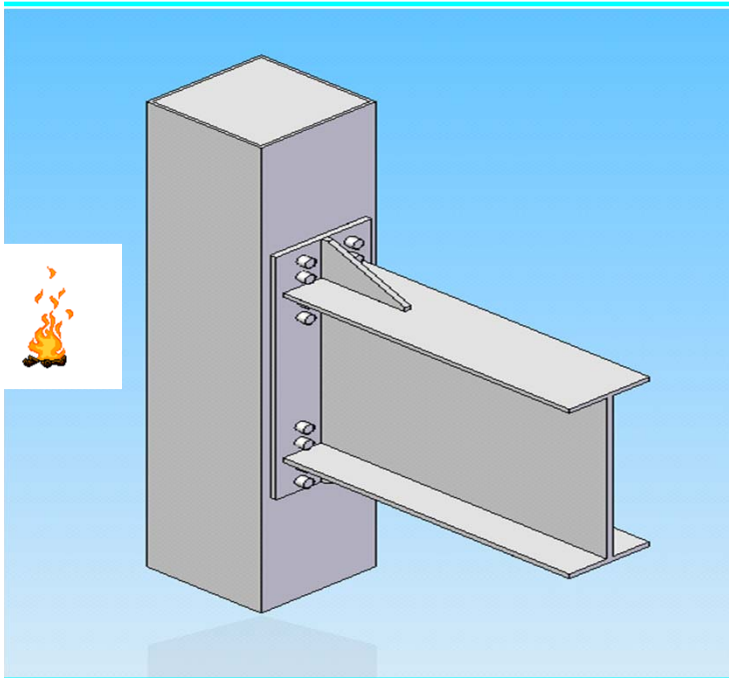
**Aesthetics – slim, thin, complex shapes, curvatures and customized textures**

## Mechanical properties

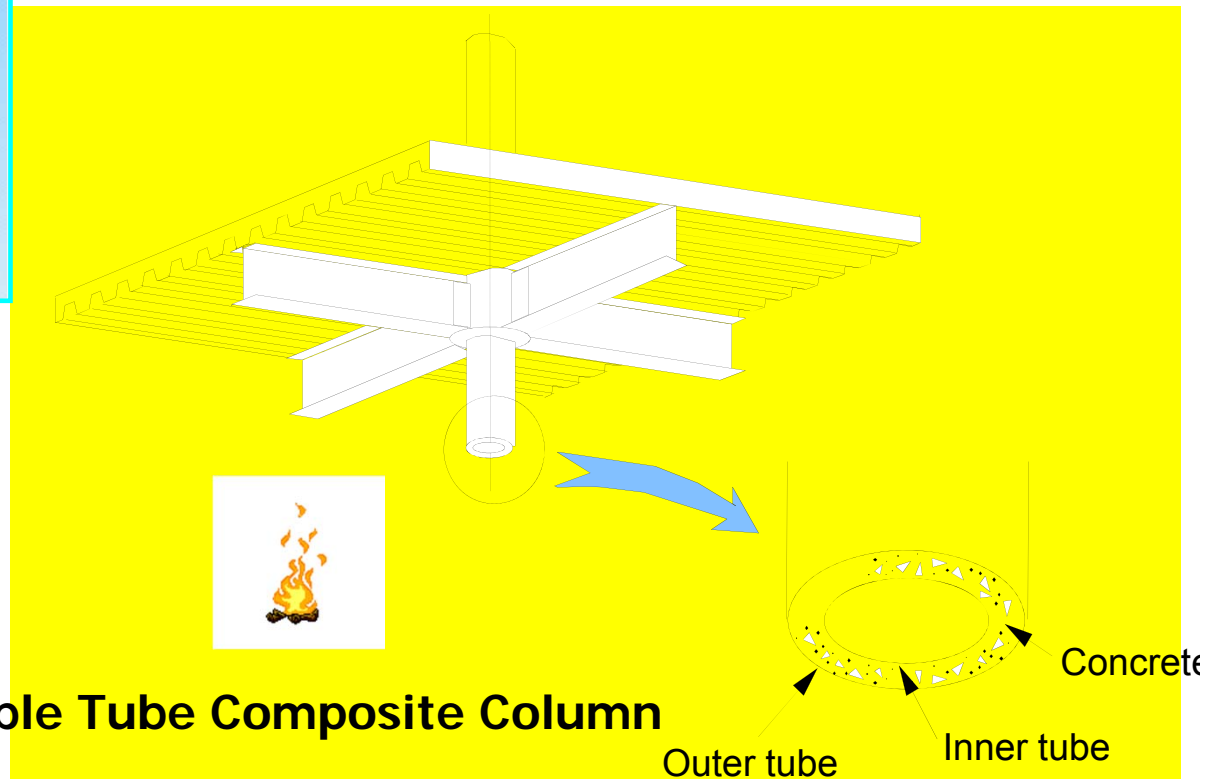
24hours strength	> 50MPa
28days strength	150 – 200 MPa
Tensile strength	> 8MPa
Flexural strength	15 – 30MPa
Elastic modulus	50 – 60GPa
Poission ratio	0.20
Shrinkage	400 – 600 x10 <sup>-6</sup>
Creep coefficient	0.2 – 0.5
Specific gravity	2.5 – 2.6

This unique combination of superior properties facilitates the ability to create innovative designs with new shapes that are thinner, lighter and more economical.

# Fire tests on UHSC composite columns

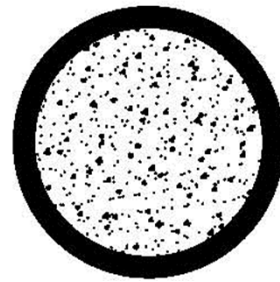
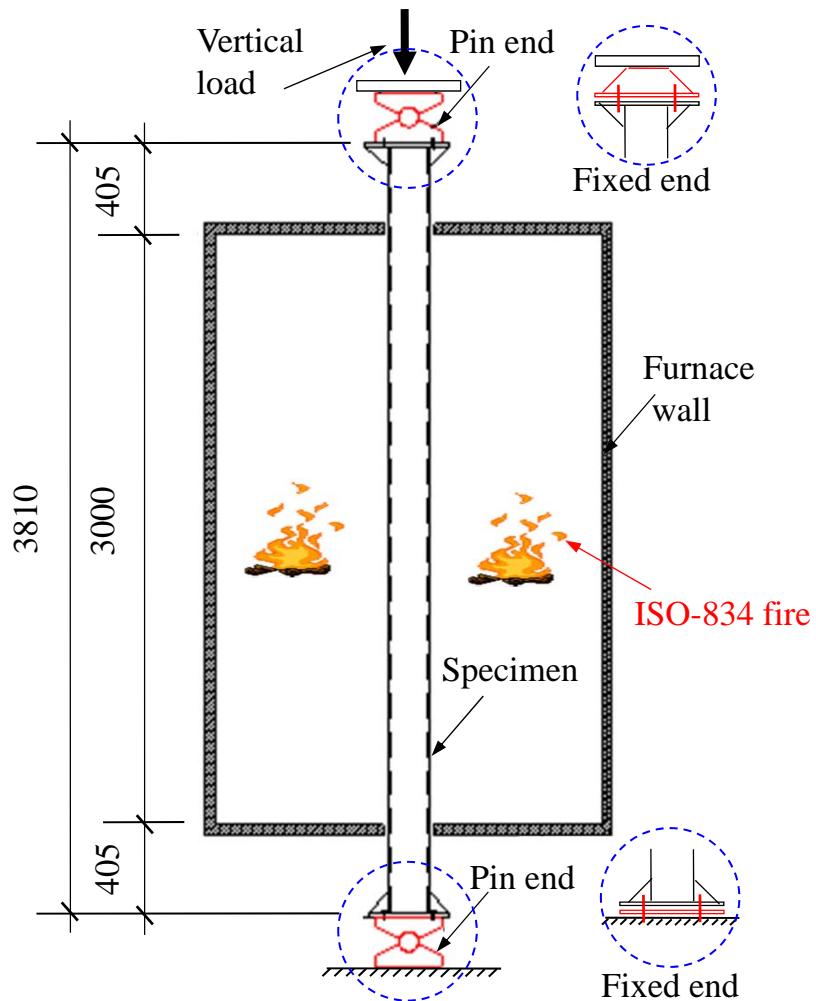


Single tube composite column

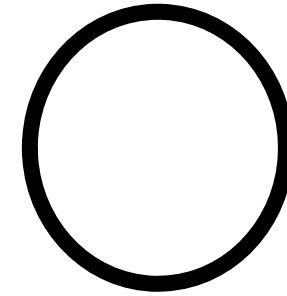


Double Tube Composite Column

# Fire Performance of Composite Column Versus Steel Column



Composite column



Steel column



Pin end



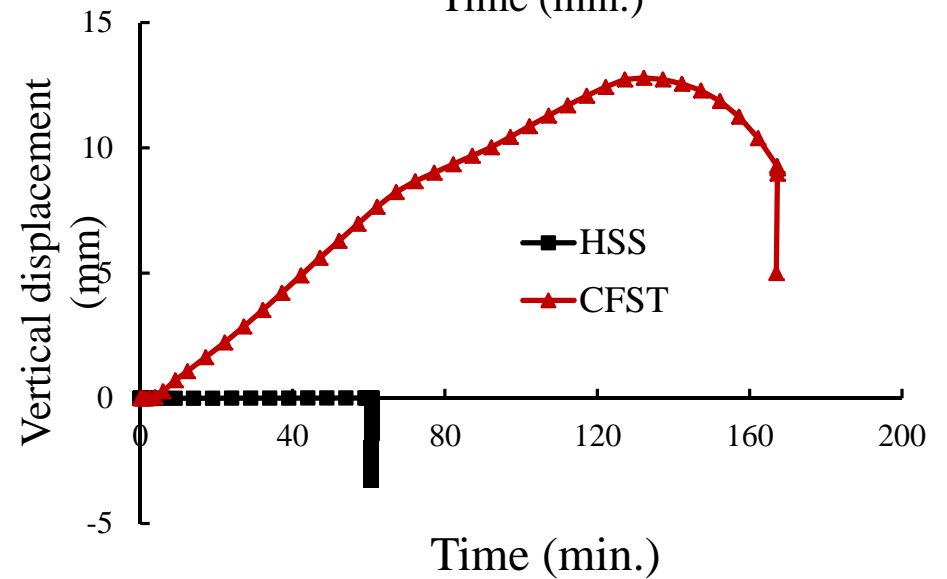
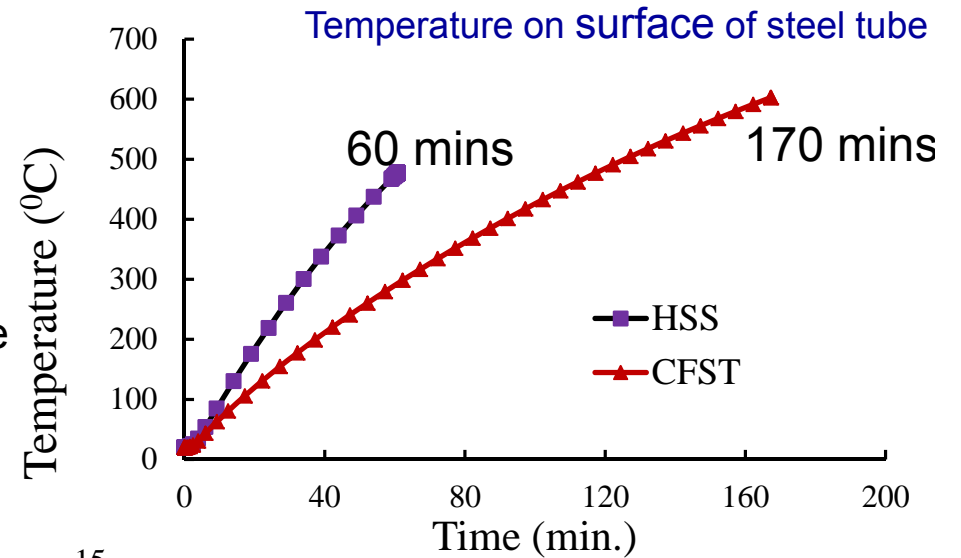
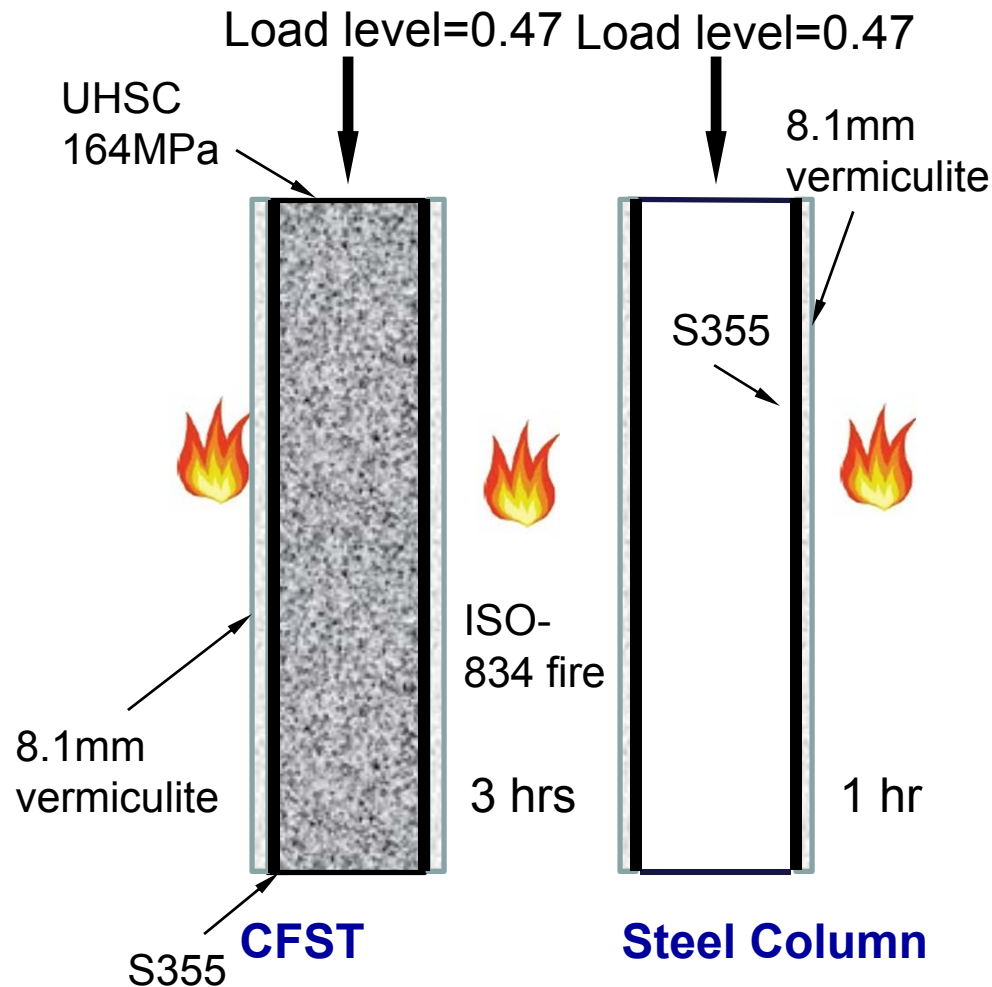
Fixed end

# Fire Resistance Performance of Circular Column

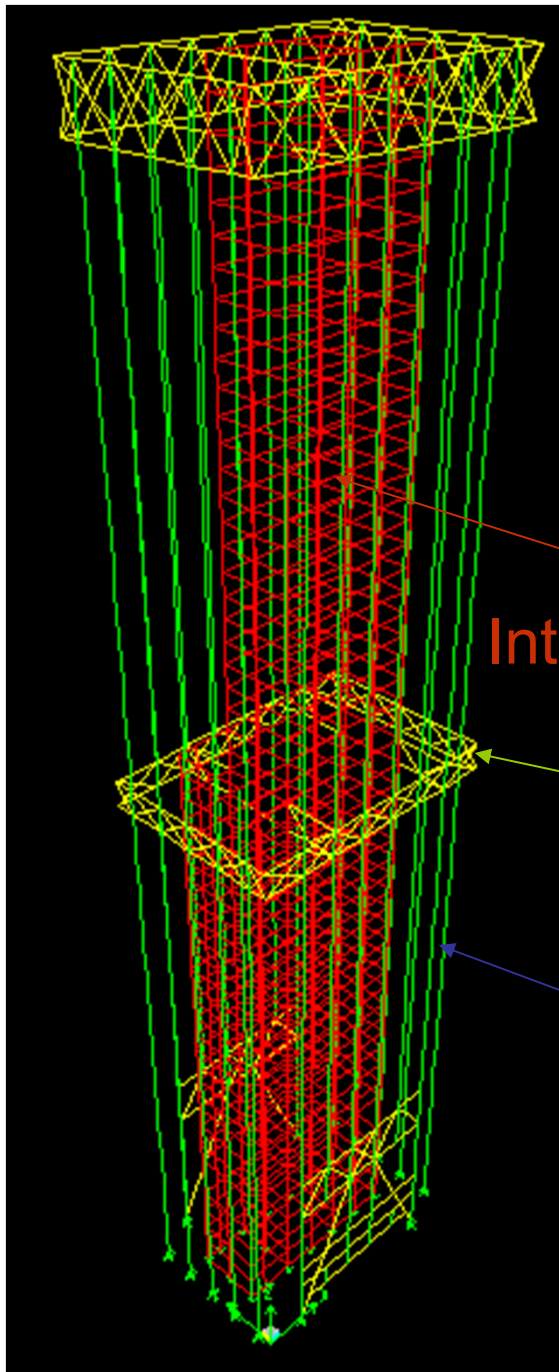
Comparison : Circular CFST  $\Leftrightarrow$  Circular HSS

Same tube size CHS 219.1X16

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



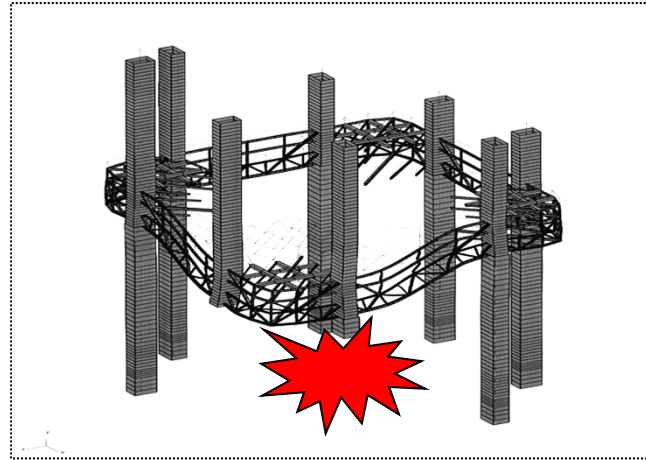
# Progressive Collapse due to Accidental Loads – impact, blast, fire etc



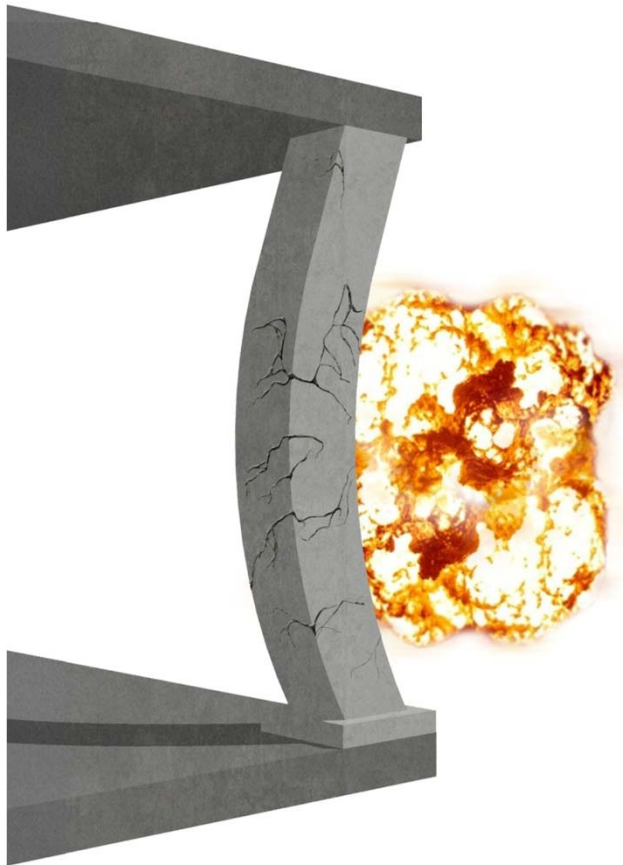
Internal Core

Belt and outrigger

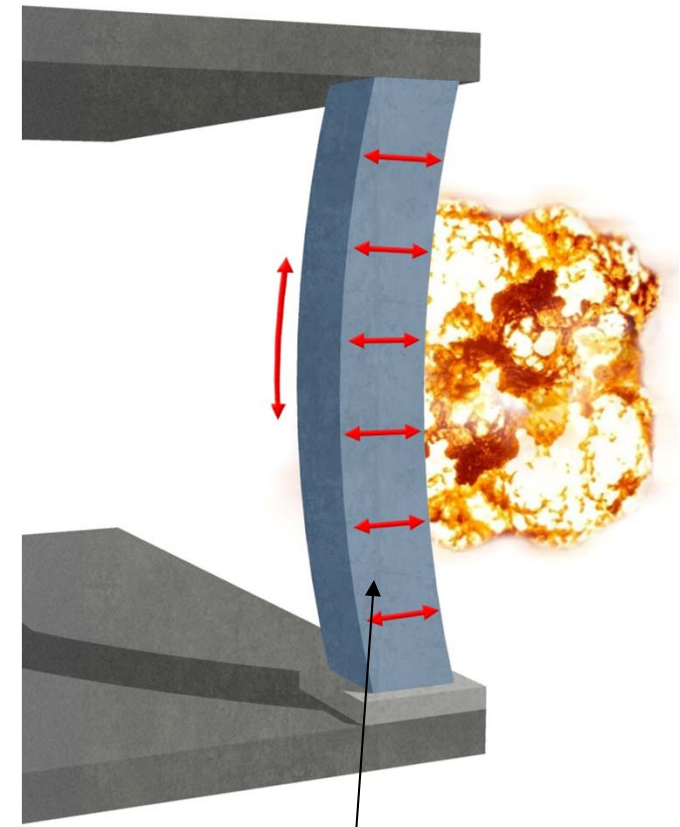
Exterior columns



# Columns Subject to Blast

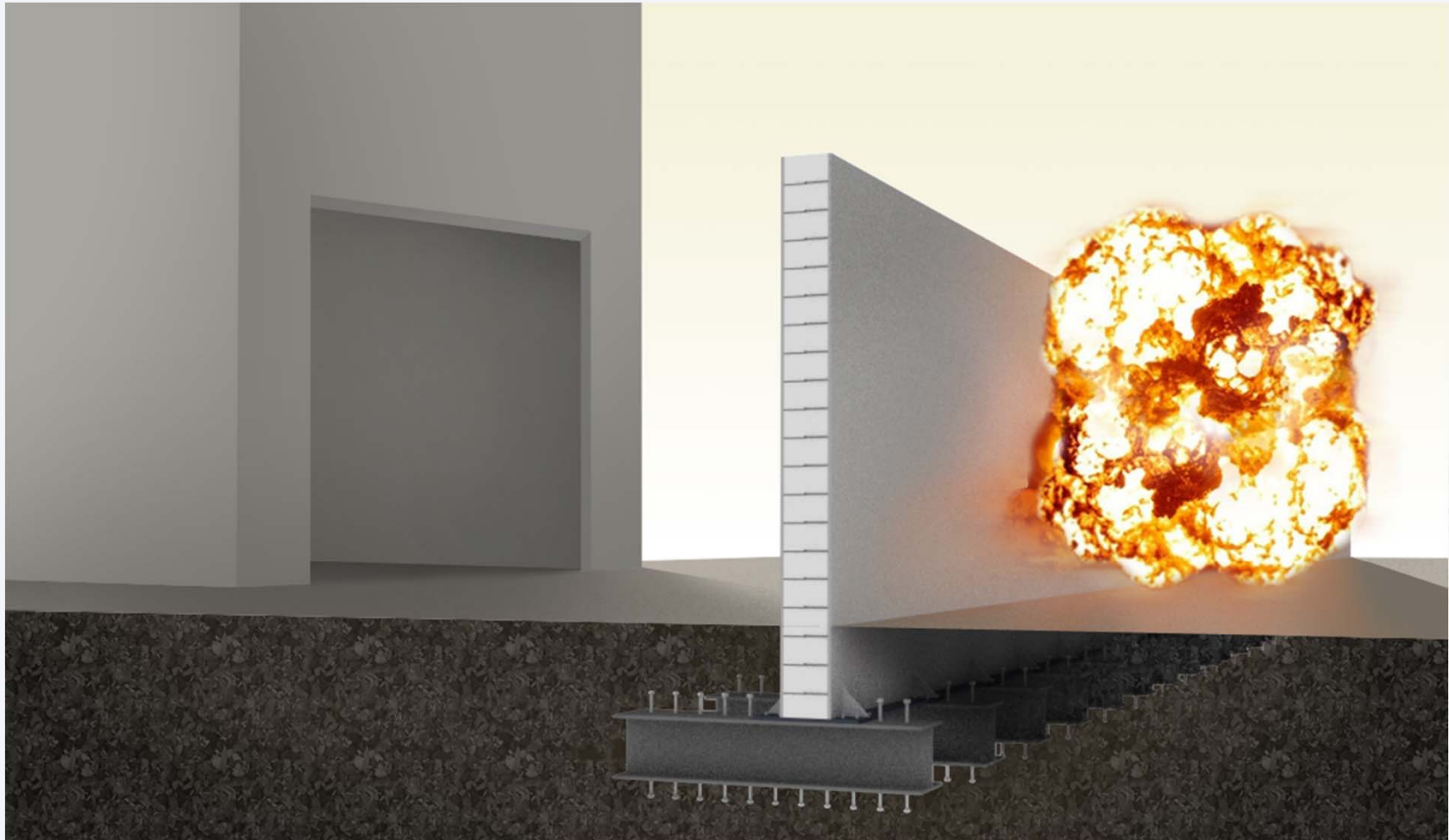


Conventional RC Columns– Cracks and spalling; may involve flying debris

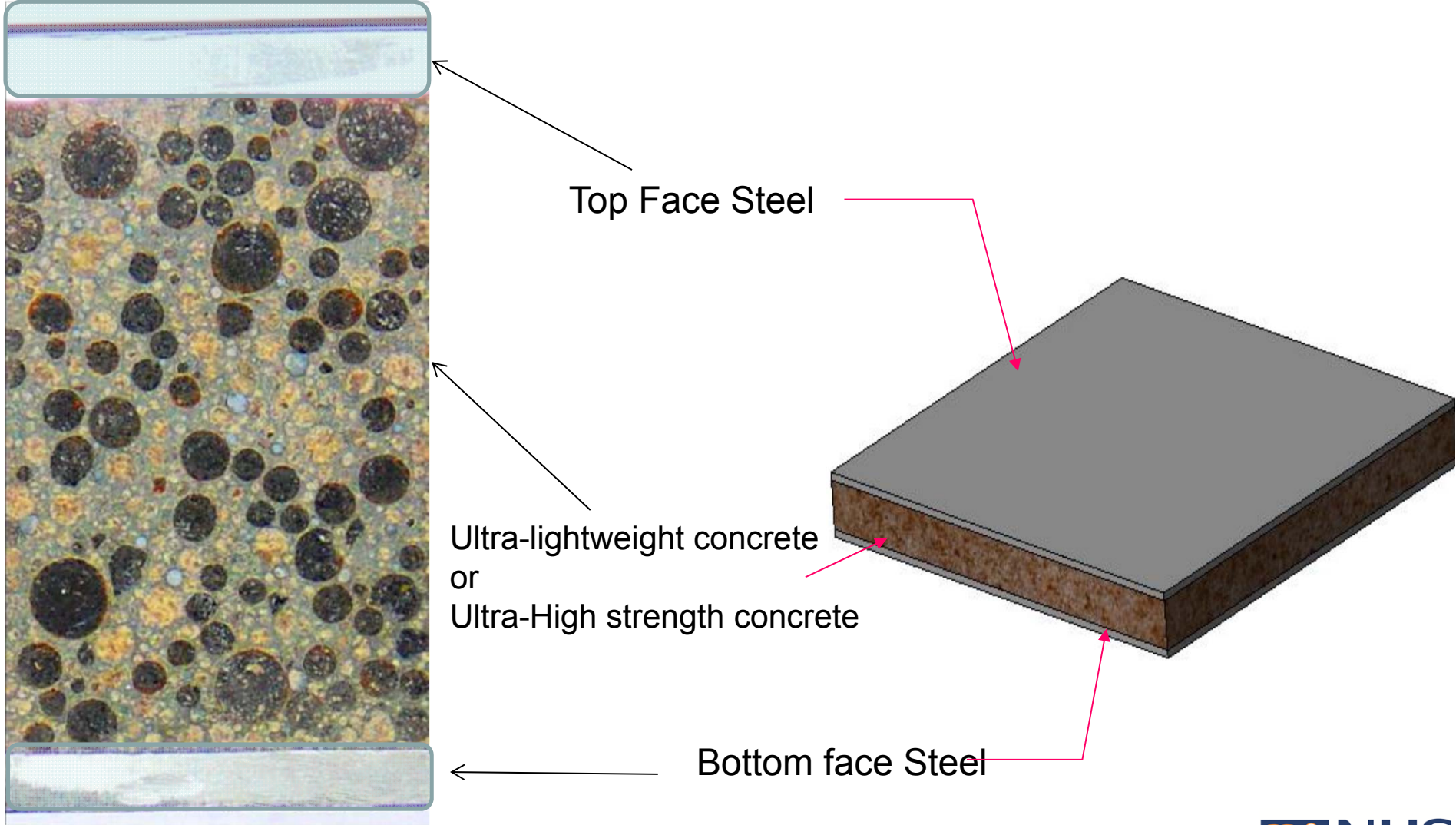


Concrete filled tubular member-  
**Concrete is confined**

# Design of Blast Protection Barrier

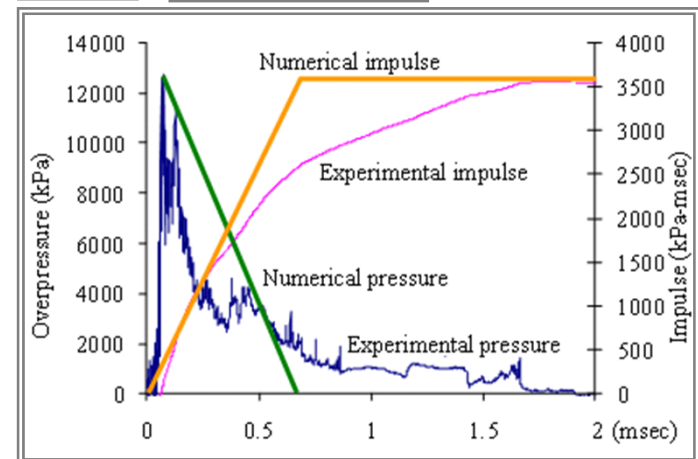
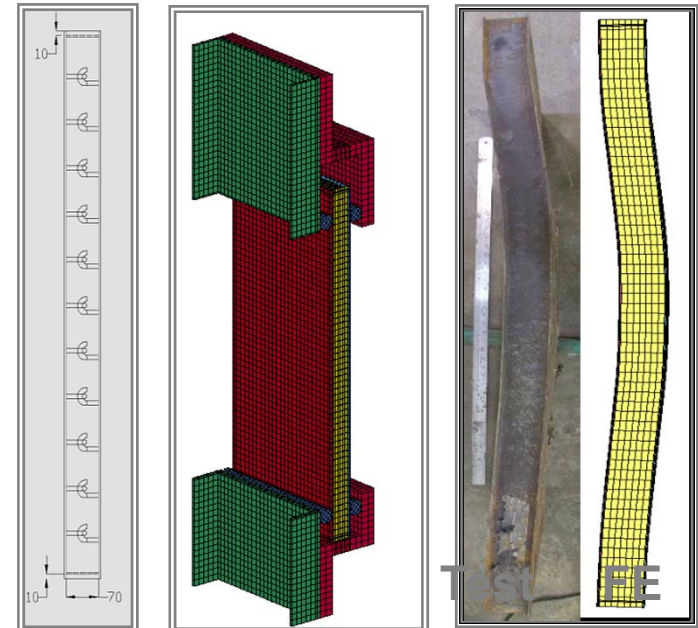
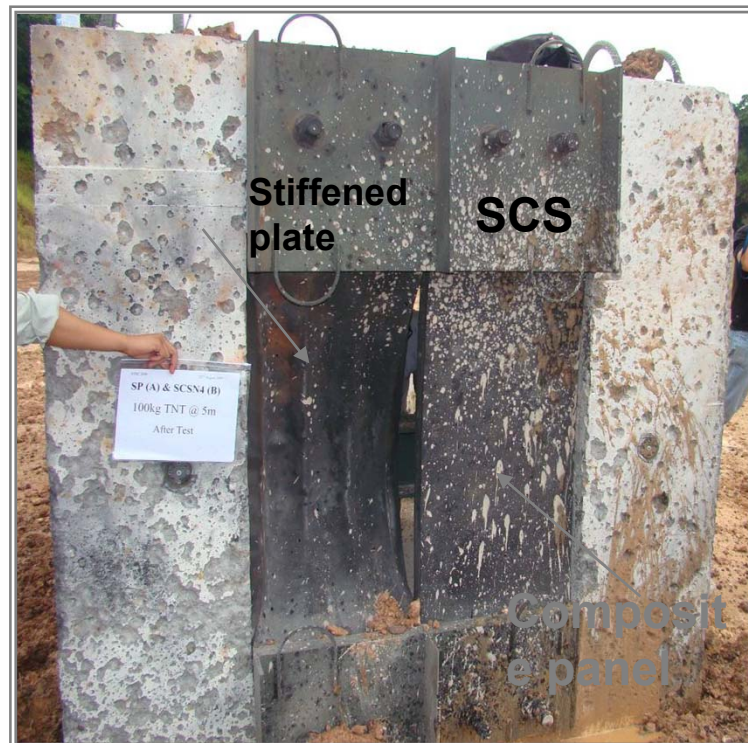
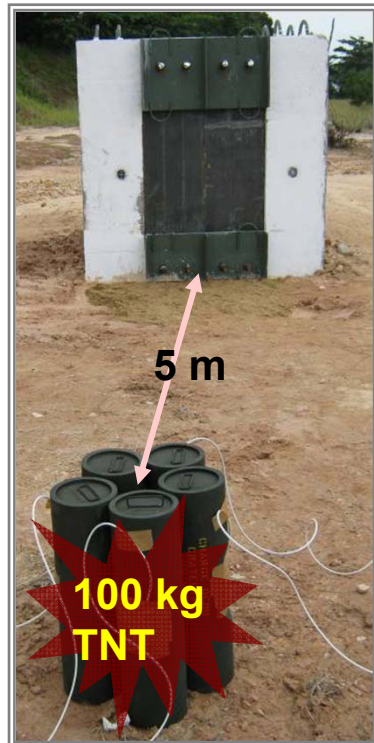


# Sandwich SCS Composite Panels

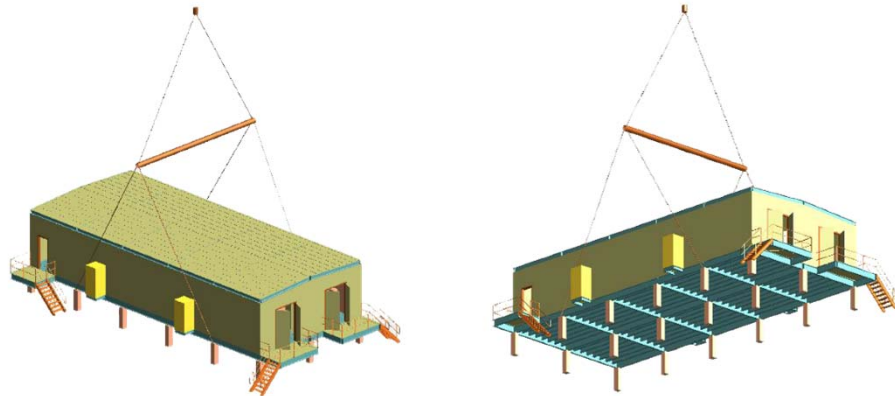


# Blast and Fire Resistance of SCS Composites Panels

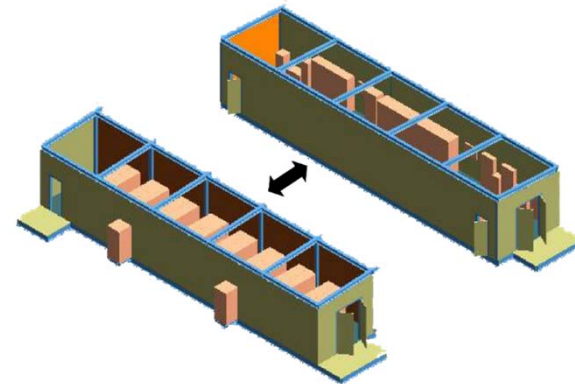
- Blast tests on composites and stiffened steel plates
- Integrated numerical analysis on blast and fire hazards afterwards



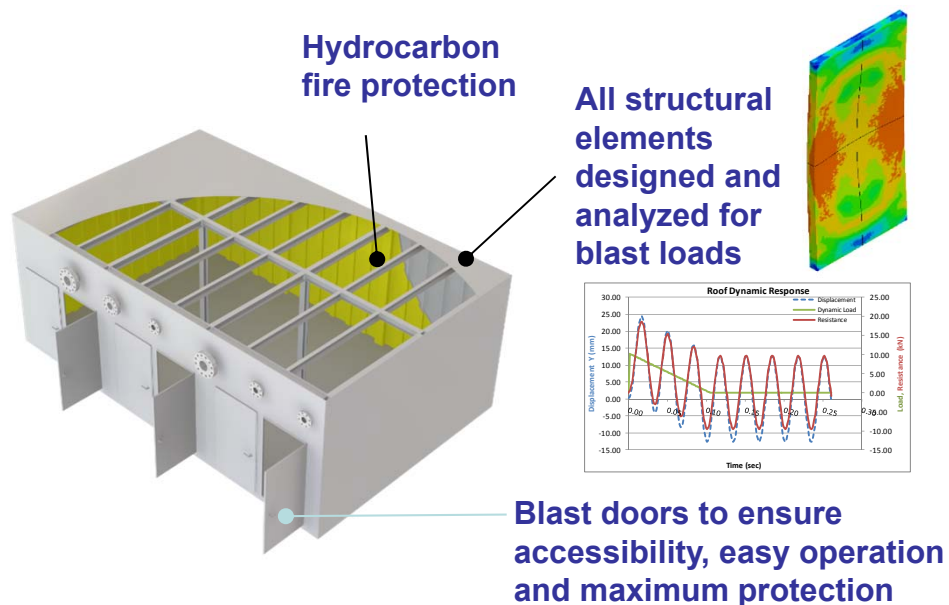
# Prefabricated Blast Resistant Module



Lifting of prefabricated prefinished blast resistant module



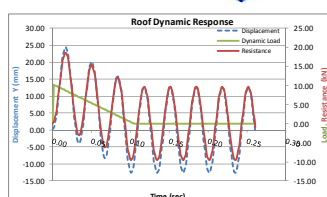
Split modular plan with temporary wall for transportation



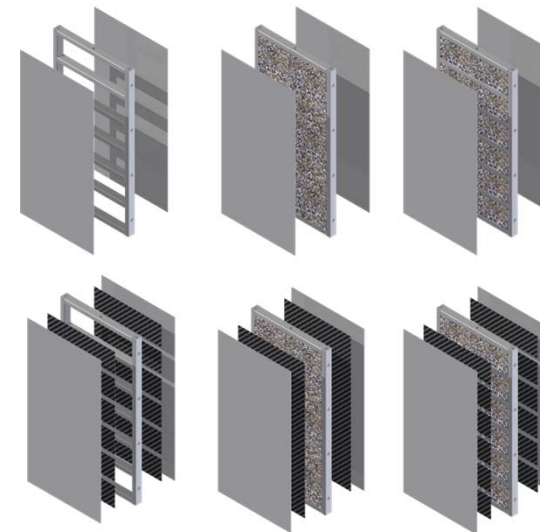
**Hydrocarbon fire protection**

**All structural elements designed and analyzed for blast loads**

**Blast doors to ensure accessibility, easy operation and maximum protection**



Time (sec)	Displacement (mm)	Dynamic load	Resistance
0.00	0.00	0.00	0.00
0.05	15.00	15.00	15.00
0.10	0.00	0.00	0.00
0.15	-15.00	-15.00	15.00
0.20	0.00	0.00	0.00
0.25	15.00	15.00	15.00
0.30	0.00	0.00	0.00
0.35	-15.00	-15.00	15.00
0.40	0.00	0.00	0.00
0.45	15.00	15.00	15.00
0.50	0.00	0.00	0.00
0.55	-15.00	-15.00	15.00
0.60	0.00	0.00	0.00
0.65	15.00	15.00	15.00
0.70	0.00	0.00	0.00
0.75	-15.00	-15.00	15.00
0.80	0.00	0.00	0.00
0.85	15.00	15.00	15.00
0.90	0.00	0.00	0.00
0.95	-15.00	-15.00	15.00
1.00	0.00	0.00	0.00



Novel material systems incorporating steel, high performance cementitious grout and FRP

# Upgrade of standard 40ft container to blast resistant and bullet proof modules

