SINGAPORE INSTITUTE OF TECHNOLOGY

Difference between Hot-Formed and Hot-Finished Steel Structural Hollow Sections

Chiew Sing-Ping
Professor and Programme Director of Civil Engineering
SINGAPORE INSTITUTE OF TECHNOLOGY

23 February 2017

Outline

1 Introduction

2 Experimental investigation

3 Test results

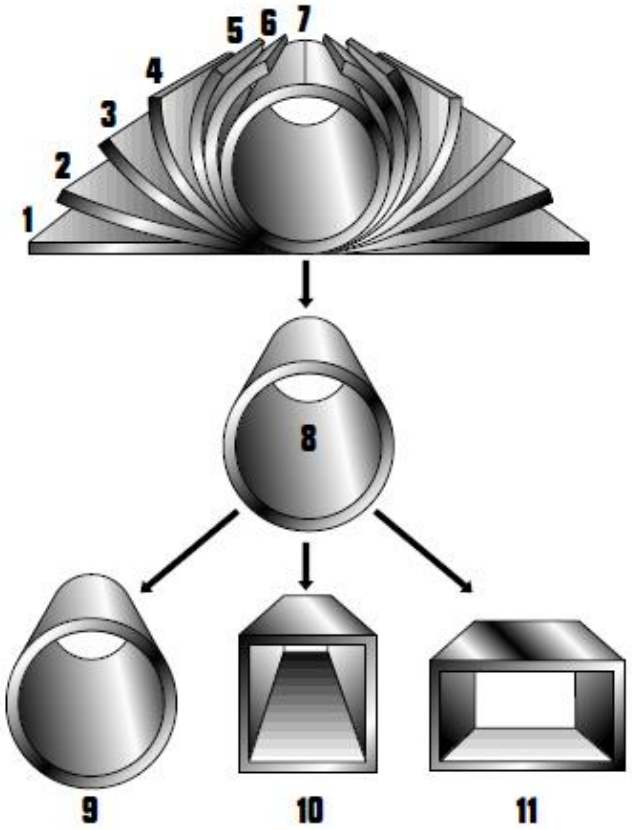
4 Conclusions

SINGAPORE INSTITUTE OF TECHNOLOGY

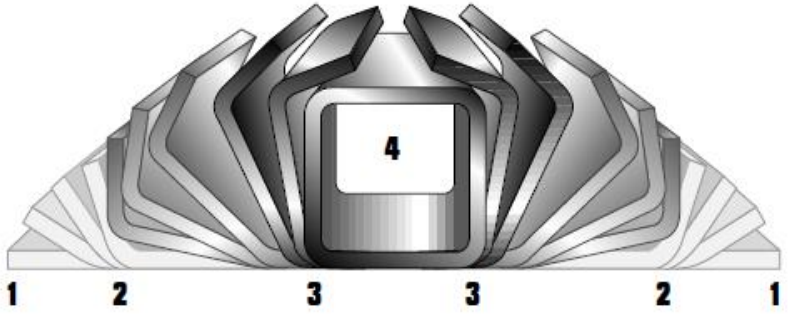
1. Introduction

1.1 Typical manufacturing methods for hollow sections
1.2 Comparison among common hollow sections
1.3 Objectives of current study

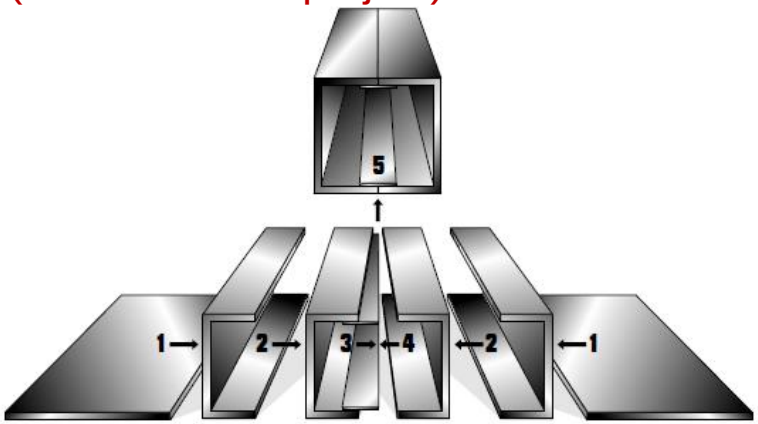
1.1 Manufacturing methods for structural hollow sections



1, Electric Resistance Welding Process



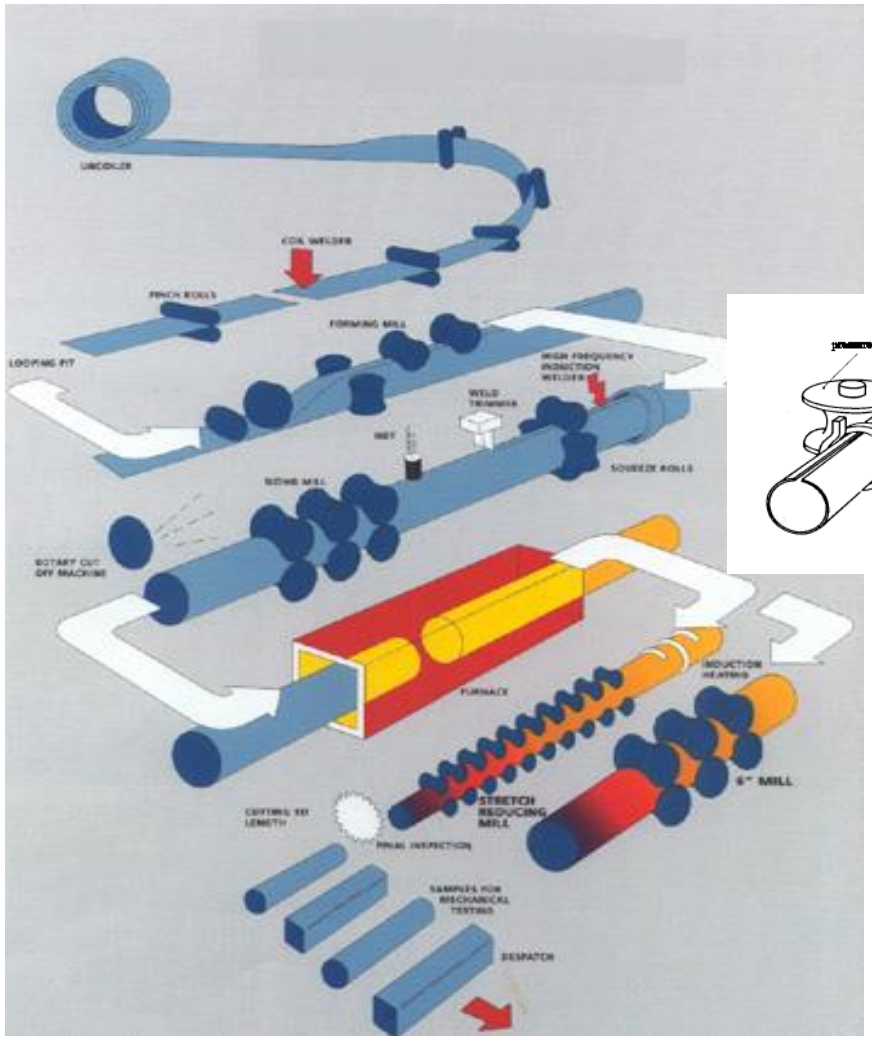
2, Form-Square Weld-Square Process
(Studied in this project)

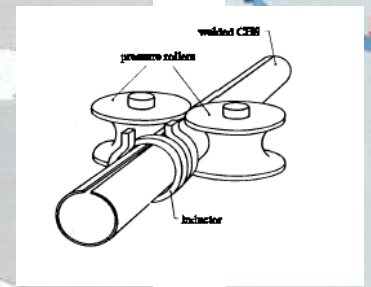


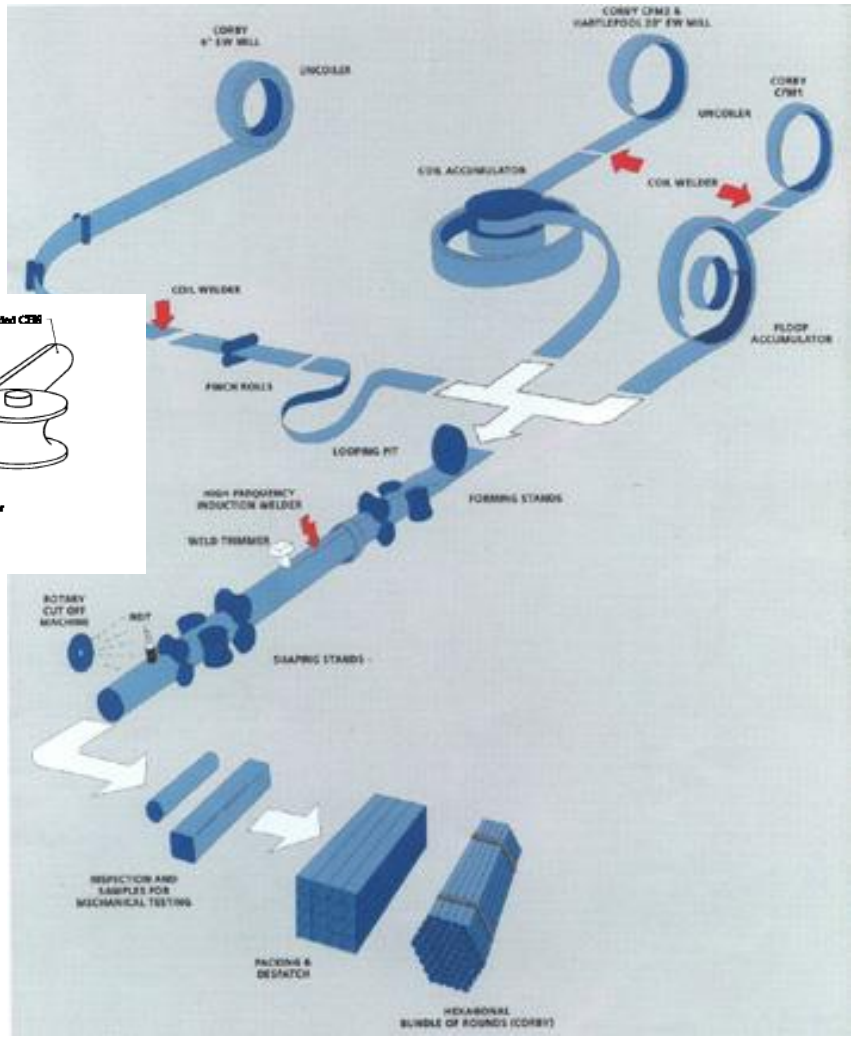
3, Submerged Arc Weld Process

SINGAPORE INSTITUTE OF TECHNOLOGY

Hot-Formed vs. Cold-Formed







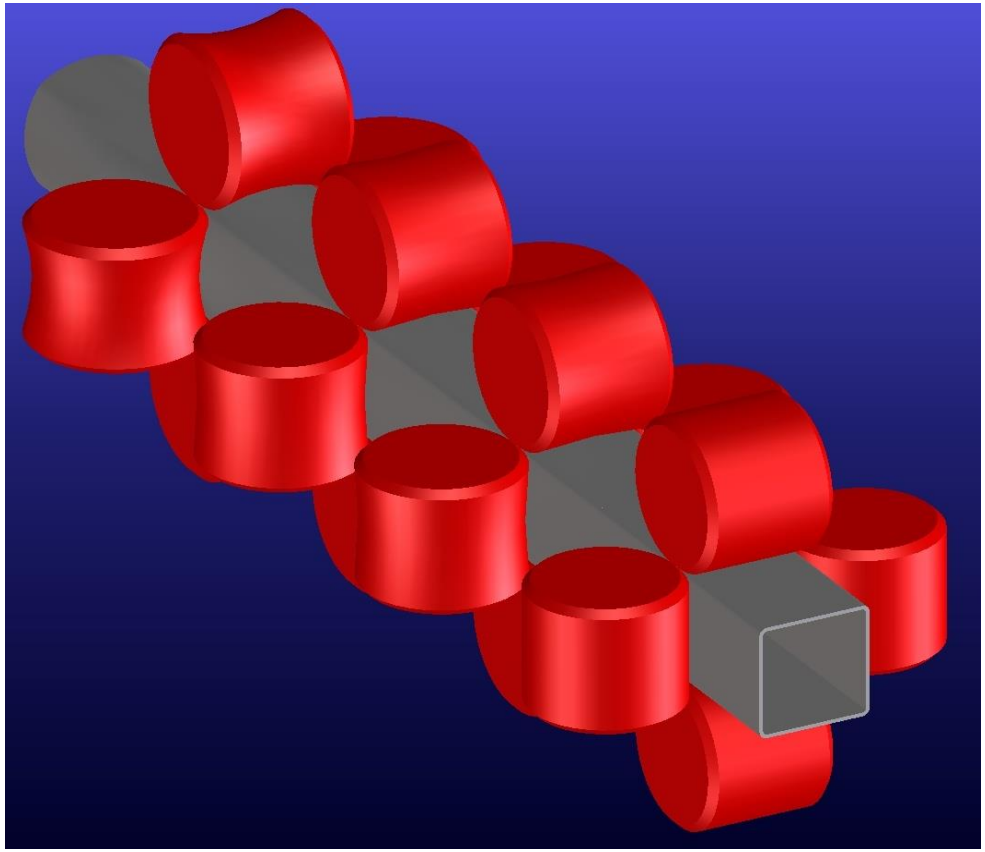
Hot-Formed

Cold-Formed

SINGAPORE INSTITUTE OF TECHNOLOGY

Re-forming into rectangular hollow sections

Usually comprises 4 conventional squeeze-roller stands



SINGAPORE INSTITUTE OF TECHNOLOGY

1.2 Theoretical differences due to strain histories and thermal actions

hot-formed & hot-finished

- Tight corner profile
- Homogeneous material properties
- Good ductility
- Low residual stress (annealed)
- BS EN 10210

Cold-formed

- Large corner radius
- High degree of cold working
- High residual stress (bending and welding)
- higher strength but lower ductility
- Potential corner cracking
- BS EN 10219

SiT SINGAPORE INSTITUTE OF TECHNOLOGY

Desired properties of structural steel

- Strength – ability to carry load
- Ductility – ability to sustain permanent deformation without loss of strength
- Toughness – ability to absorb damage without fracture
- Weldability – ability to transfer load

1.3 Objectives of current study

- Comparison on the physical and mechanical properties of hot-formed, hot-finished and cold-formed rectangular hollow sections

a. Geometrical differences
b. Chemical compositions and weldability
c. Strength and ductility
d. toughness
e. Residual stresses

SINGAPORE INSTITUTE OF TECHNOLOGY

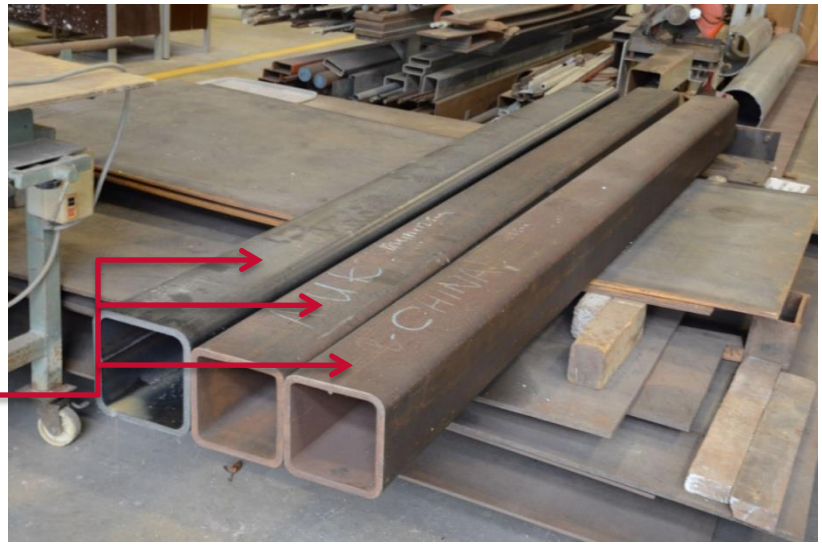
2. Experimental investigations

2.1 Geometrical measurement
2.2 Chemical composition test
2.3 Tensile test
2.4 Charpy v-notch impact test
2.5 Residual stress measurement

Research target

- The hot-formed and hot-finished hollow sections:
  180mm x 180mm x 12.5mm
- The cold-formed hollow sections:
  200mm x 200mm x 12.5mm

Similar in appearance, different in properties

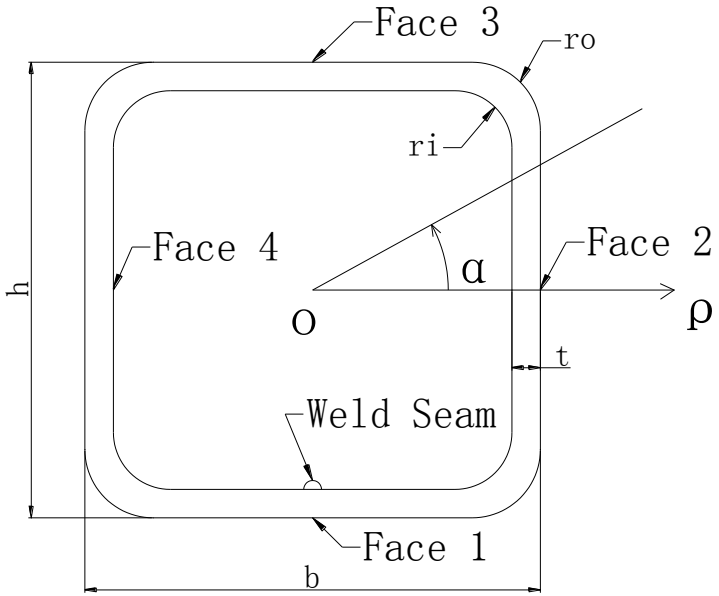


SINGAPORE INSTITUTE OF TECHNOLOGY

2.1 Geometrical measurements

To check the surface delivery conditions and dimensional tolerances according to the corresponding production standards.

a. Surface discontinuities (imperfections and defects);
b. Geometrical sizes;
c. Geometrical parameters.



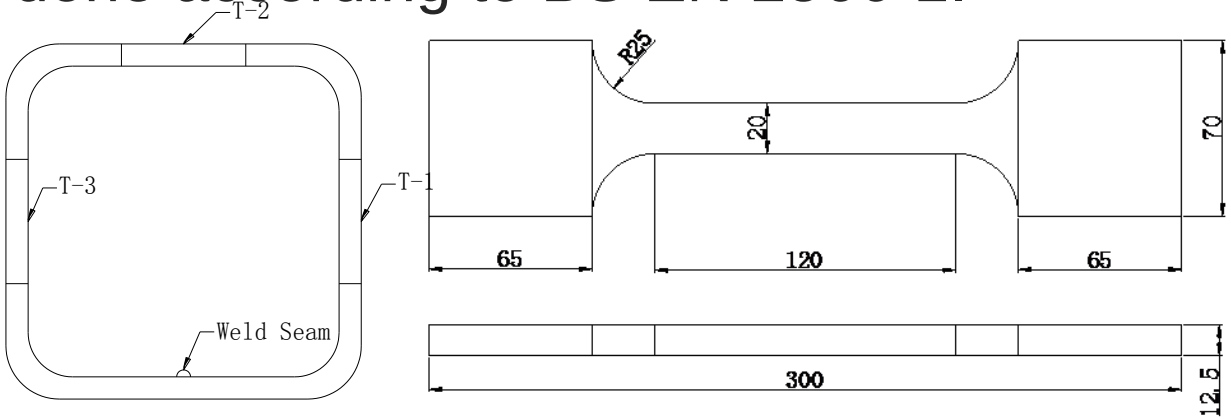
2.2 Chemical composition test

- OES method: Optical Emission Spectroscopy Method by *SPECTROTEST*
- Capable of detecting: C, Mn, Cu, P, S, Al, Ti, Si, Cr, Mo, V, and Ni.

2.3 Tensile coupon tests

- Coupons from the center area of Face 2, 3 and 4 and tested according to EN 10002-1:2001.
- Measurement: strain gauge and extensometer.
- Original gauge length: 80mm.
- Conversion of elongation from non-proportional gauge length to proportional gauge length done according to BS EN 2566-1.

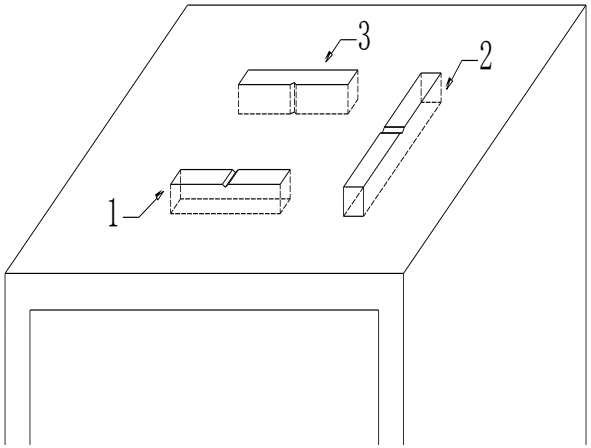
$$5.65\sqrt{S_0}$$



SINGAPORE INSTITUTE OF TECHNOLOGY

2.4 Charpy v-notch impact test

- Three tests for each hollow section
- Standard charpy specimens: 55x10x10 mm
- Test temperature: -20 ºC



2.5 Residual stress measurements

- (1) Sectioning test

  Measuring the opening distance after sectioning

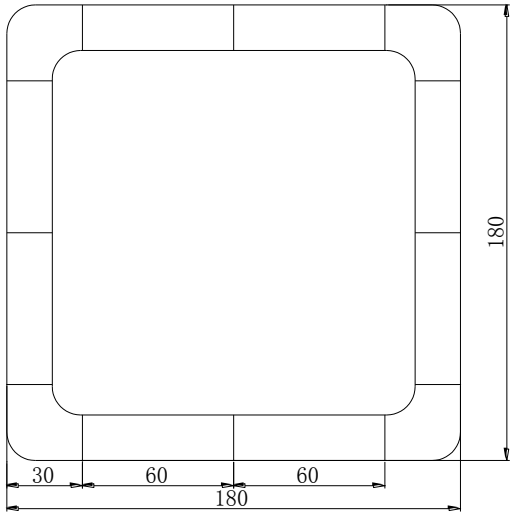
- (2) Semi-destructive hole drilling method

  Residual stresses within 2mm deep and 1mm diameter hole were measured along the perimeter

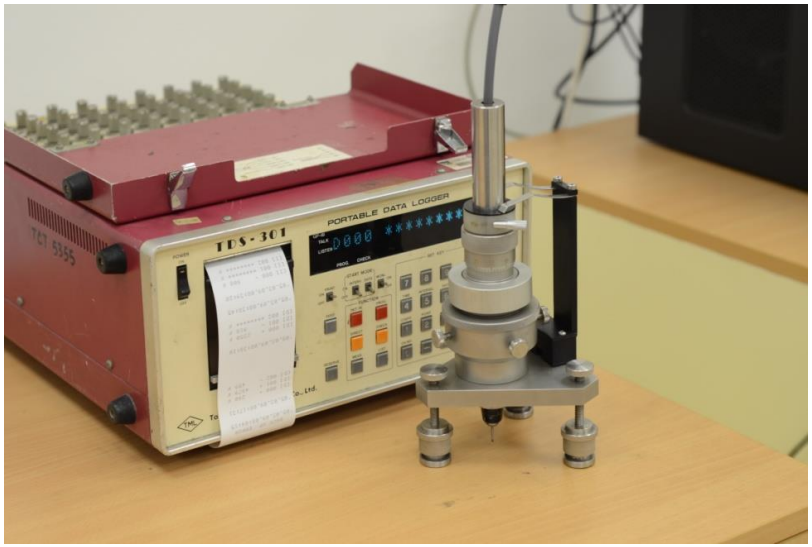
  Released strains by drilling were recoded for further analysis

Sectioning test

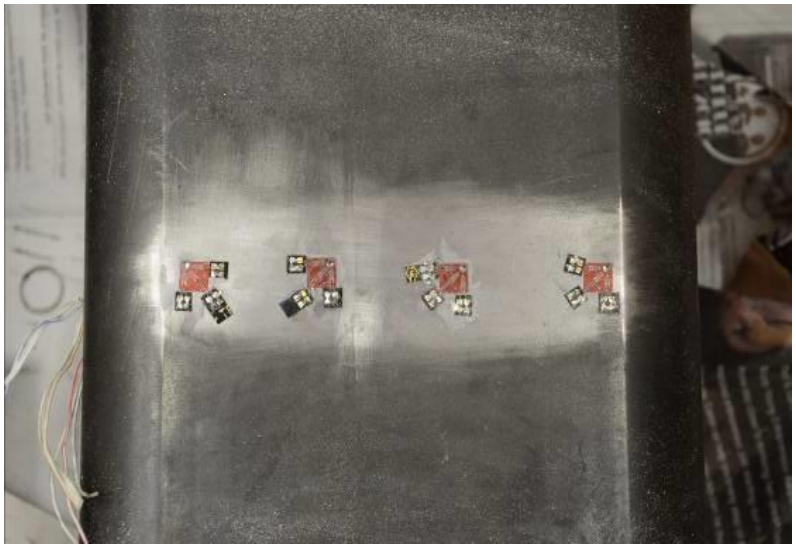
- Length of the specimen: 200mm
- 3 cuts on each side
- Cutting depth: 170mm



Hole drilling test



RS-200 and data logger



Drilled holes on the specimen

3. Test results

3.1 Geometrical measurements
3.2 Chemical composition
3.3 Strength and ductility
3.4 Toughness
3.5 Residual stresses

3.1 Geometrical measurements

- No surface discontinuities that were not allowed in EN 10210 and EN 10219 were found.
- The cold-formed hollow section had the largest corner radii, followed by hot-finished and hot-formed hollow sections.

Hollow sections	b_m (mm)	t_m (mm)	$r_{o,m}$ (mm)	$r_{i,m}$ (mm)	2r	$r_{o,m}/t_m$	$r_{i,m}/t_m$
Cold-formed	200.53	12.76	30.00	21.75	15.72	2.35	1.71
Hot-formed	180.27	12.72	25.00	12.13	14.17	1.97	0.95
Hot-finished	180.34	12.88	26.75	14.00	14.00	2.08	1.09

3.2 Chemical compositions

	C	Mn	Cu	P	S	Al	Ti	Si	Cr	Mo	V	Ni	CE
Cold-formed	0.082	0.970	0.022	0.029	0.004	0.02	<0.001	0.160	0.026	0.006	0.004	0.020	0.280
BS EN 10219	≤0.2	≤1.6	≤0.35	≤0.04	≤0.04	≥0.02	≤0.05	≤0.6	≤0.3	≤0.2	≤0.05	≤0.8	≤0.45
Hot-formed	0.140	1.330	0.034	0.031	0.009	0.045	<0.001	0.340	0.033	0.008	0.006	0.026	0.432
Hot-finished	0.120	1.300	0.017	0.033	0.006	0.029	<0.001	0.17	0.024	0.010	0.009	0.016	0.376
BS EN 10210	≤0.2	≤1.6	≤0.35	≤0.04	≤0.04	≥0.02	≤0.03	≤0.6	≤0.3	≤0.1	≤0.2	≤0.8	≤0.45

$$CE = \%C + \left(\frac{\%Mn + \%Si}{6}\right) + \left(\frac{\%Cr + \%Mo + \%V}{5}\right) + \left(\frac{\%Cu + \%Ni}{15}\right)$$

SINGAPORE INSTITUTE OF TECHNOLOGY

Summary for chemical test

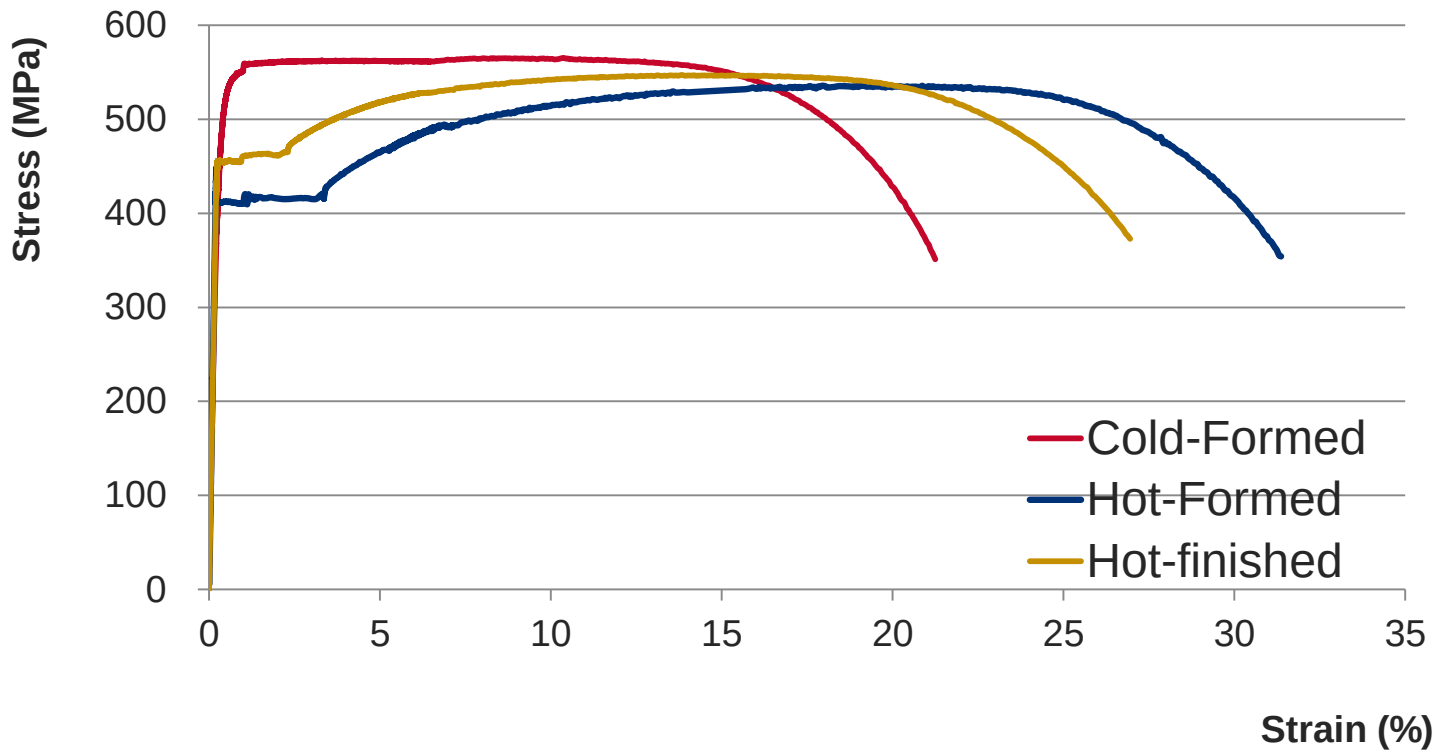
- All the elements contents were strictly within the ranges required by the corresponding standards.
- The composition of the three sections are similar, except for small differences in C, Mn and Cu.
- For weldablity in terms of CE values, cold-formed > hot-finished > hot-formed in this case.

3.3 strengths and ductility

Samples		Yield Stress (Mpa)	Tensile Stress (Mpa)	Tensile ratio	Elongation (%)
Cold-formed	F-2	529.3	562.2	1.06	23
	F-3	511.0	551.6	1.08	22
	F-4	523.0	563.7	1.08	22
Hot-formed	F-2	411.8	536.1	1.30	30
	F-3	403.4	521.9	1.29	31
	F-4	416.7	535.1	1.28	32
Hot-finished	F-2	440.9	531.2	1.20	27
	F-3	527.4	588.3	1.12	22
	F-4	454.3	546.0	1.20	28

SINGAPORE INSTITUTE OF TECHNOLOGY

Typical stress-strain curves



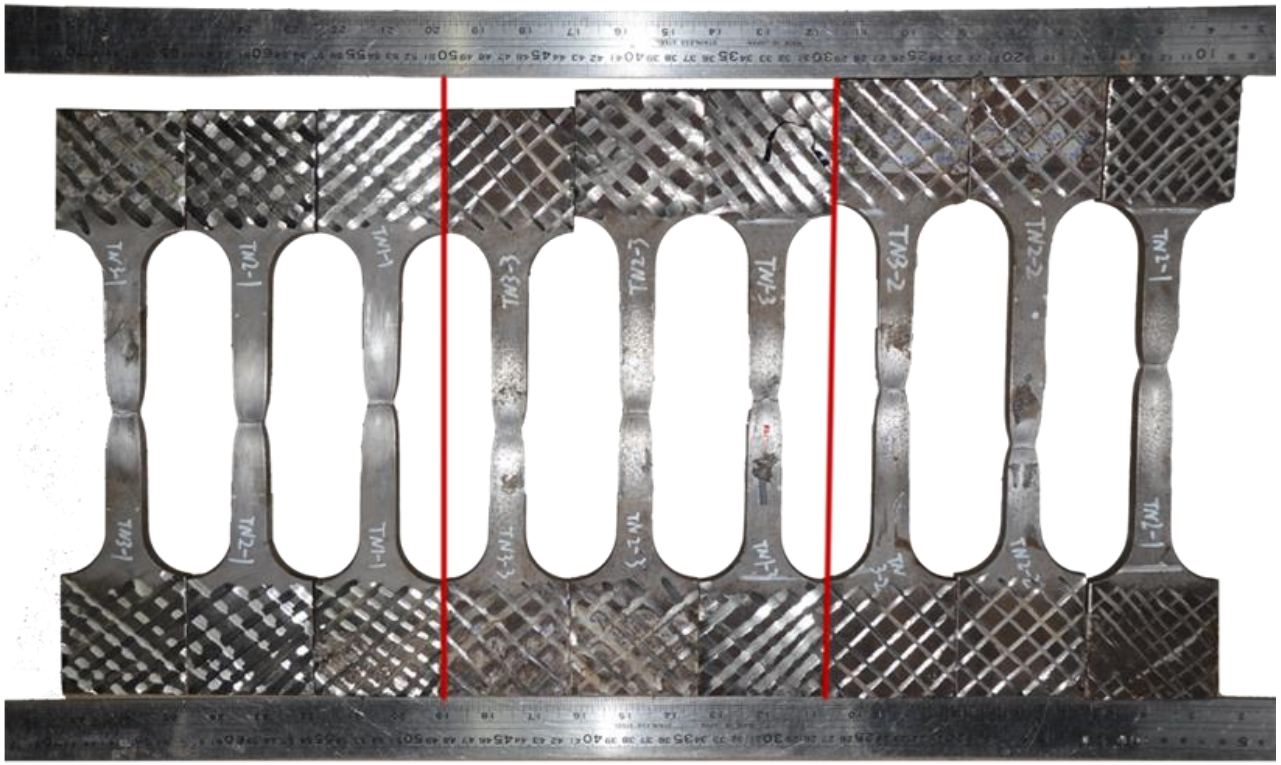
Nominal yield strengths:

Cold-formed steel: *the 0.2% offset strength*

Hot-formed and Hot-finished: *lower yield strength*

SINGAPORE INSTITUTE OF TECHNOLOGY

Ductility in forms of Elongation



Cold-formed Hot-finished Hot-formed

SINGAPORE INSTITUTE OF TECHNOLOGY

Summary for tensile test

- cold-formed: the highest yield and tensile strength but the worst ductility
- hot-formed: the lowest strength yet the best ductility
- Hot-finished: between the other two

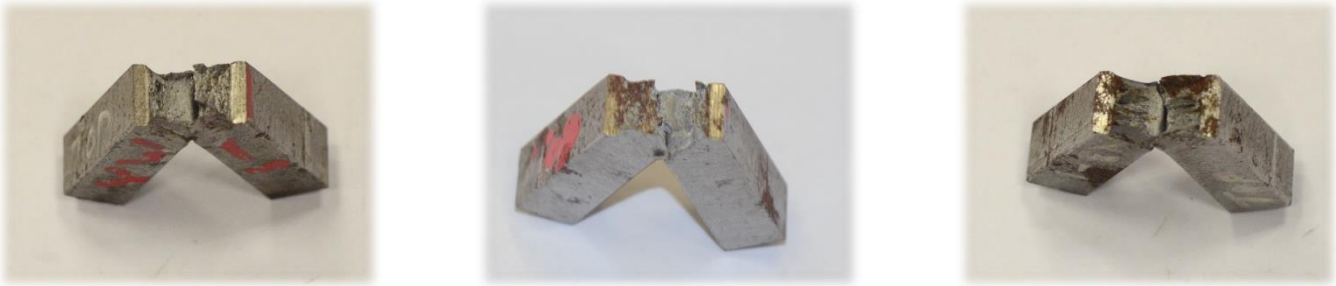
- No obvious inhomogeneity in face strengths and ductility was observed (less than 5% except for face 3 of the hot-finished section)

3.4 Toughness

Samples and Positions		Energy (J)	Average (J)	EN 10210 & EN 10219
Cold-formed S355J2H	1	168.6	172.8	Min. 27 J
	2	255.4		
	3	94.4		
Hot-formed S355J2H	1	56.9	127.4	
	2	280.2		
	3	45.0		
Hot-finished S355J2H	1	143.1	135.1	
	2	190.5		
	3	71.7		

SINGAPORE INSTITUTE OF TECHNOLOGY

Chapy v-notch impact test result



Specimens from the cold-formed hollow section (position: 1,2,3)

Specimens from the hot-formed hollow section (position: 1,2,3)

Specimens from the hot-finished hollow section (position: 1,2,3)

SINGAPORE INSTITUTE OF TECHNOLOGY

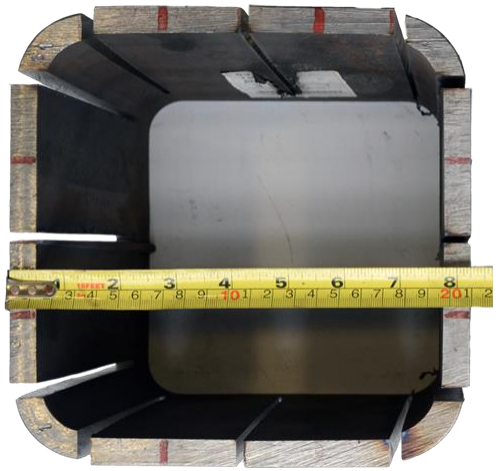
Summary for toughness

- The toughness values vary with their original positions and directions on the tubes.
- Position 2 has the highest toughness, position 1 and 3 are comparable.
- Overall, cold-formed S355J2H showed the highest toughness, while values of hot-formed and hot-finished S355J2H are also high.

3.5 Residual stresses

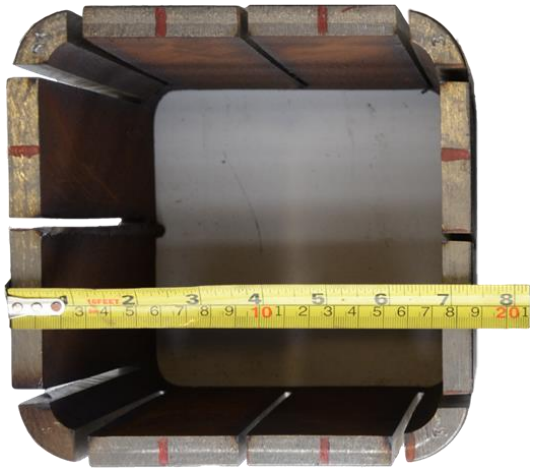
- The residual shear and axial stress distributions in terms of f_r/f_y are compared (divided by the actual yield strengths respectively)
- In accordance with geometrical symmetry, the residual stress distribution trend exhibited high repeatability with period of 90˚
- Residual stress fluctuate rapidly at corners (45, 135, 225 and 315˚) and weld seam (270˚).

Sectioning test result



Cold-formed
200mm → 210mm
(+5%)

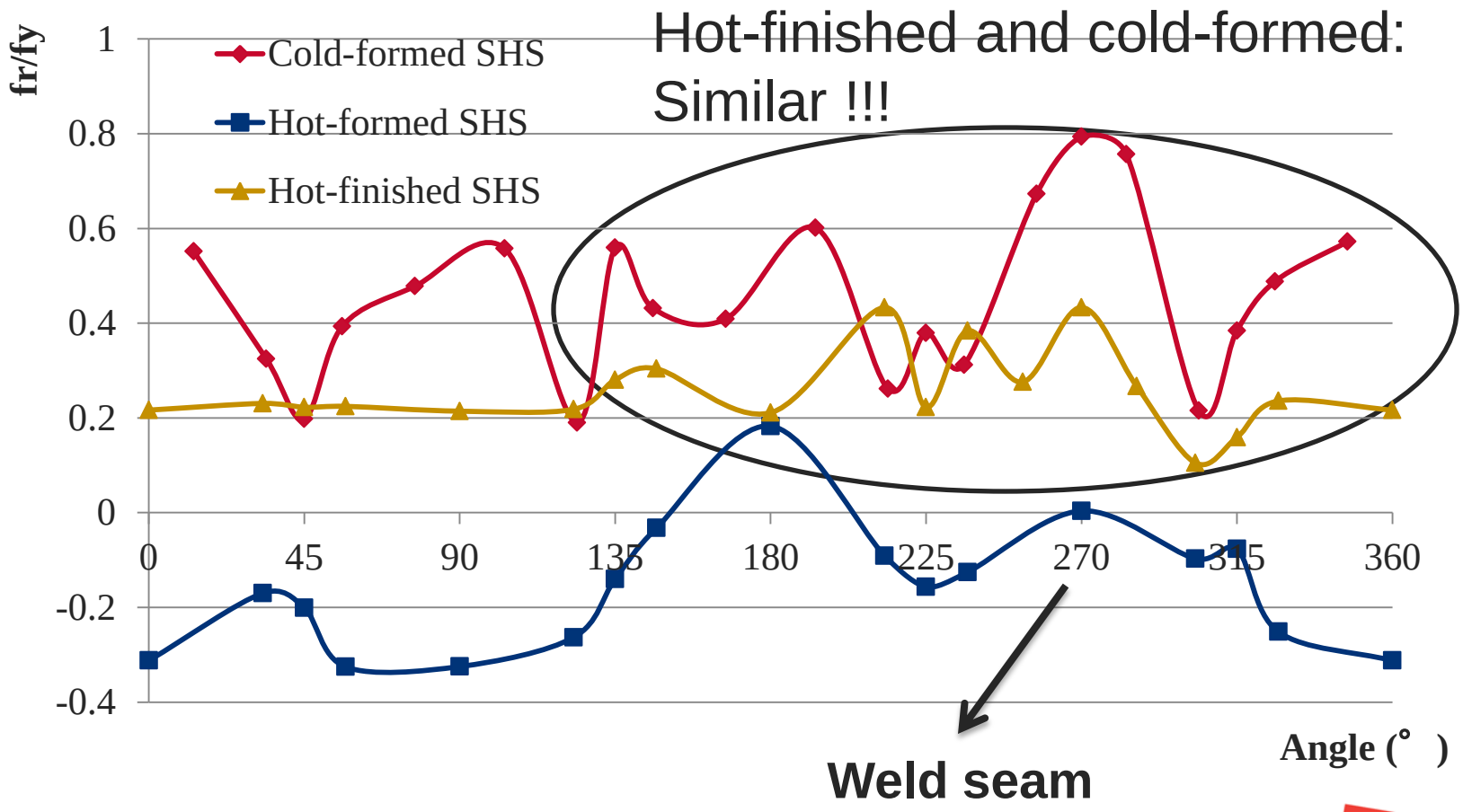
Hot-formed
180mm → 180mm
(0%)



Hot-finished
180mm → 186mm
(+3.3%)

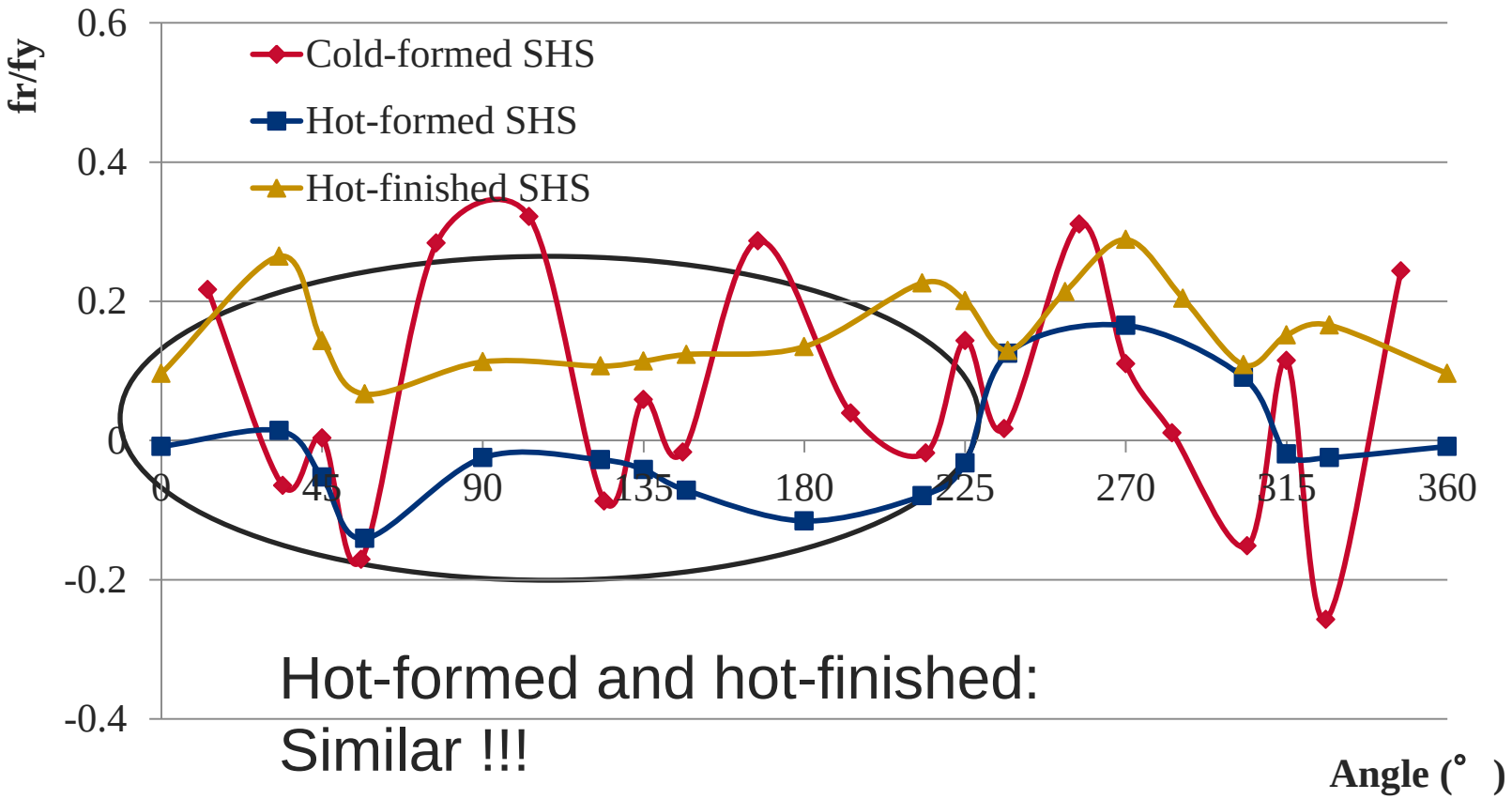
SINGAPORE INSTITUTE OF TECHNOLOGY

Residual stresses in the longitudinal direction



SINGAPORE INSTITUTE OF TECHNOLOGY

Residual stresses in the perimeter direction



Hot-formed and hot-finished: Similar !!!

SINGAPORE INSTITUTE OF TECHNOLOGY

Summary for residual stress

- Residual stress distributions in cold-formed section are highly inhomogeneous.
- The amount of residual stress:

  cold-formed>hot-finished>hot-formed
- The hot-finished section is not fully annealed as the hot-formed section

4. Conclusions (1)

- The tested three hollow sections fully comply the corresponding production standards, but they are different from each other.
- cold-formed S355J2H had the highest strength but the lowest ductility; hot-formed S355J2H had the lowest strength but the best ductility, while the hot-finished S355J2H was somewhere in between.
- The highest toughness at -20° C was attained by the cold-formed S355J2H, but the values of the three sections are comparable.

Conclusions (2)

- The cold-formed section contains the largest number of residual stress with the biggest variance, while the hot-formed contains the least.
- The residual stresses at the corners and weld seams are the largest in most cases.
- The residual stress distribution of the hot-finished section behaves similar to the cold-formed in the longitudinal direction and similar to the hot-formed in the perimeter direction.

Thank You!

SINGAPORE INSTITUTE OF TECHNOLOGY