Stainless Steel in Structures –
Fifth International Experts Seminar

SOUTHEAST UNIVERSITY

Study on the Cold Forming Effect in Cold-rolled Austenitic Stainless Steel Hollow Sections

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Outline

- Motivation and objective
- Introduction to cold rolling process
- Residual stress measurement and distribution model
- Material test and strength enhancement model
- Conclusions

1. Motivation and Objective

- Stainless steel: **Attractive new structural material**

Gateway water treatment, UK

Kunlun station of China Antarctic Research Station

Stonecutter bridge, China

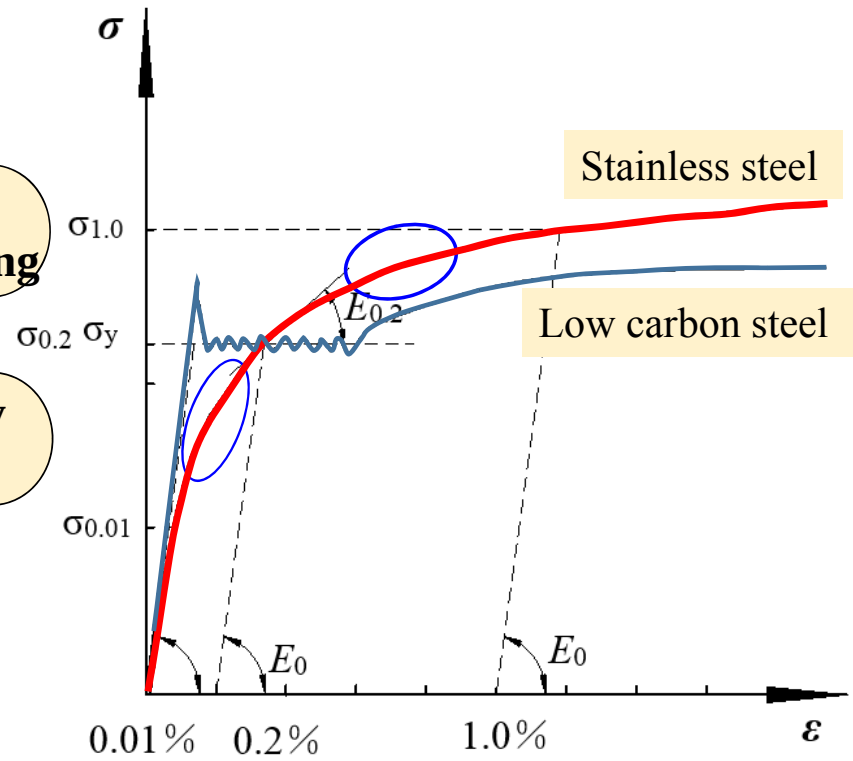
- Features: **Corrosion resistance, Architectural rendering, Cryogenic Toughness**

1. Motivation and Objective

■Material mechanical feature: **Nonlinearity**

Considerable strain hardening

***E* continuously declining**



◆Material models

✓ One-stage: Ramberg-Osgood, MacDonald

✓ Two-stage: Rasmussen, Gardner

✓ Three-stage: Quach

✓ Multi-stage: Hradil

1. Motivation and Objective

Motivation

- The mechanical state of tube used in design is not identical with the real state in current design code.
- The high initial price.

Material Nonlinearity

Cold forming

Material in annealed plate → **Material in cold formed tube**

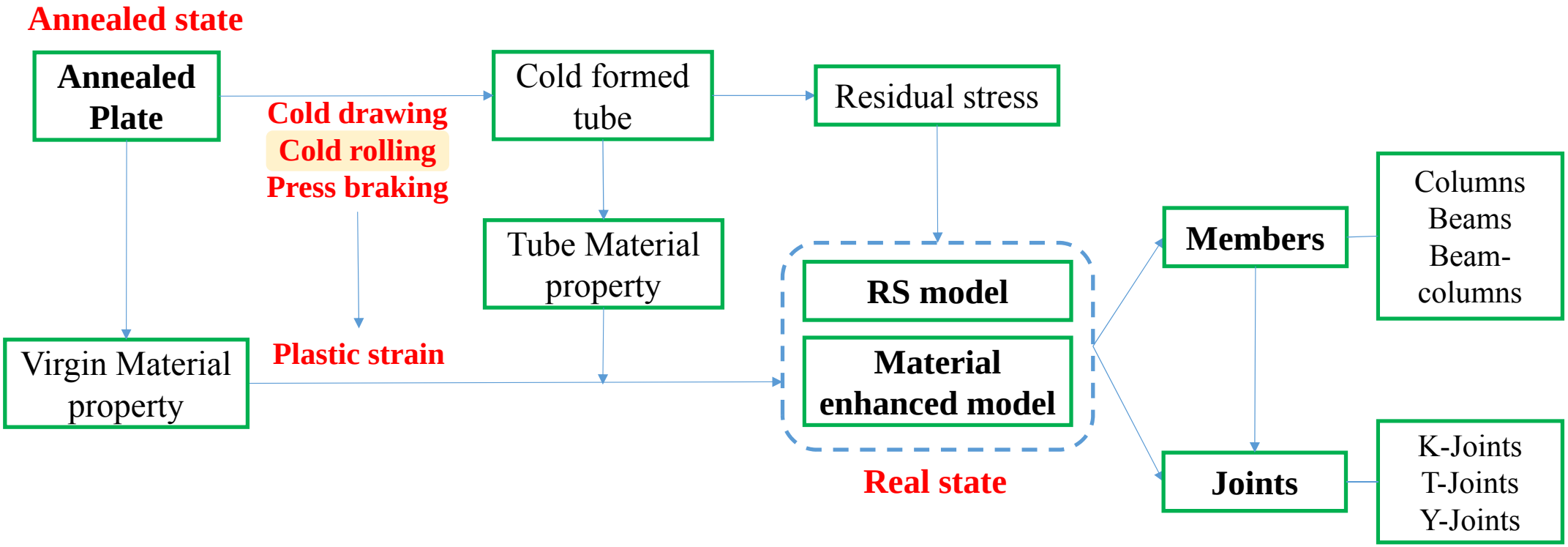
Predict

Objective

- Develop models to predicted the real initial state of mechanical properties for cold rolled cross sections to be used in design, to **save material**.

1. Motivation and Objective

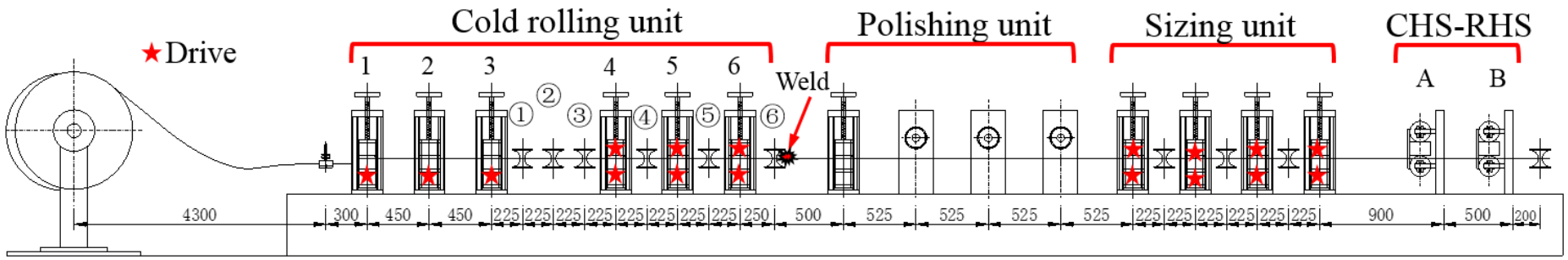
Research program



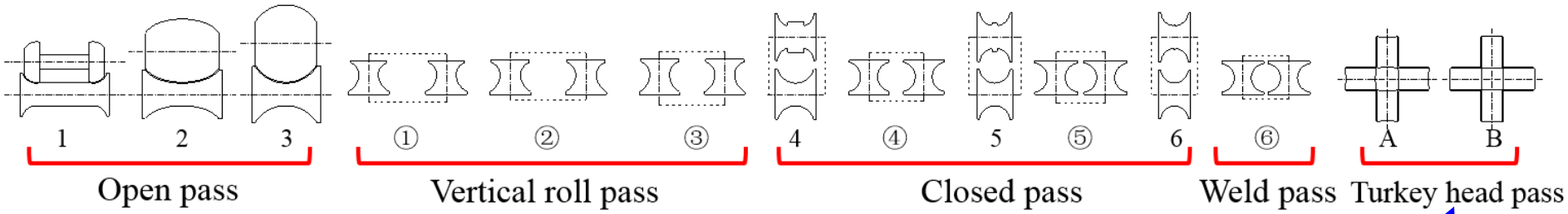
2. Introduction to Cold rolling process

- Coiled steel is passed through consecutive sets of stands, each performing only an incremental part of the bend, until the desired cross-section profile is obtained.

Stands Layout



Mill



Crush a CHS to a RHS

- ✓ Maximum Diameter about 300mm， maximum thickness about 10mm.
- ✓ Efficient, high in mill cost.

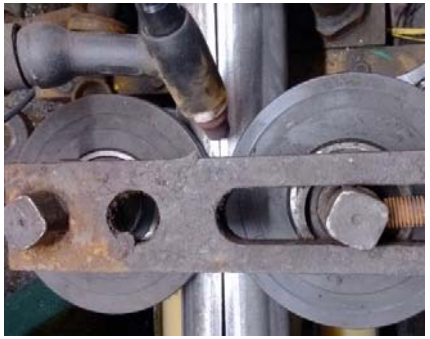
2. Introduction to Cold rolling process

Coil

Open pass

Vertical roll pass

Closed pass



Weld pass

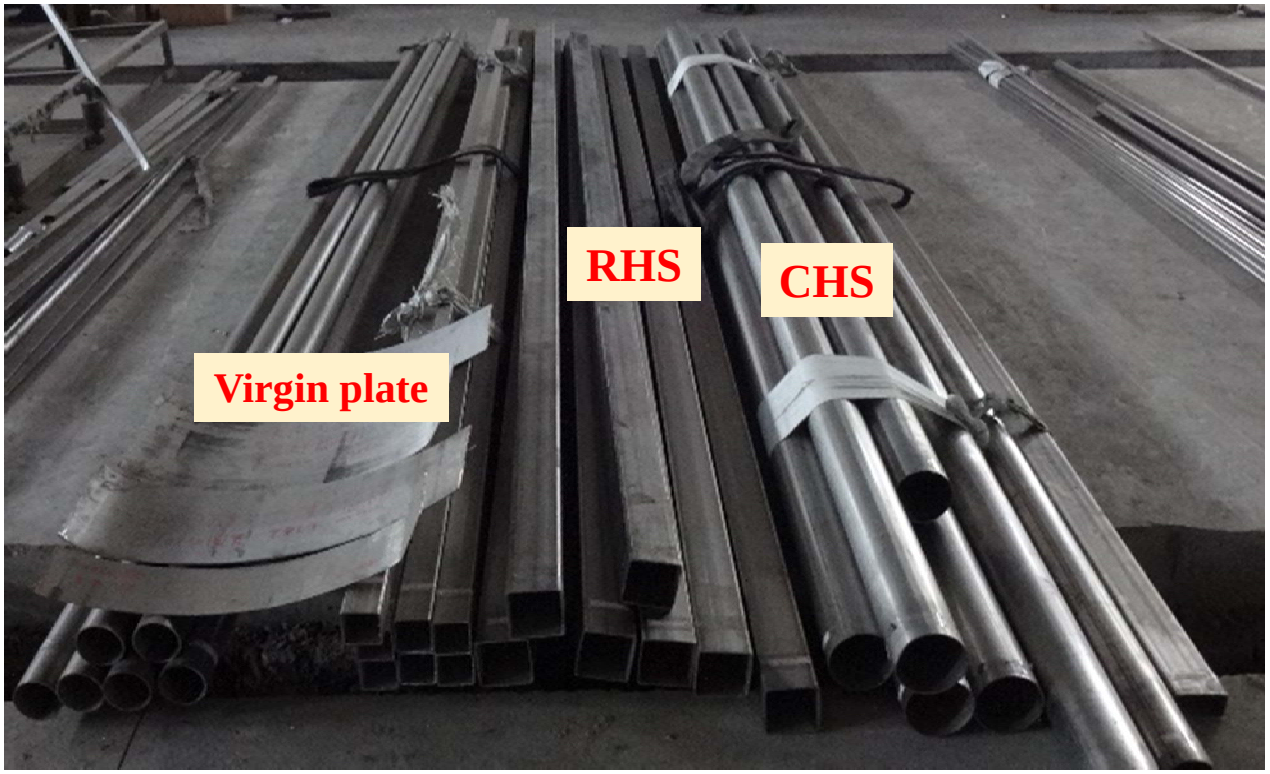
Sizing pass

Turkey head pass

CHS and RHS

2. Introduction to Cold rolling process

■Specimens source of this research program



✓ Four production lines

✓ Four CHSs, Four RHSs

G1: CHS127×3, RHS100×3

G2: CHS96×3, RHS100×50×3

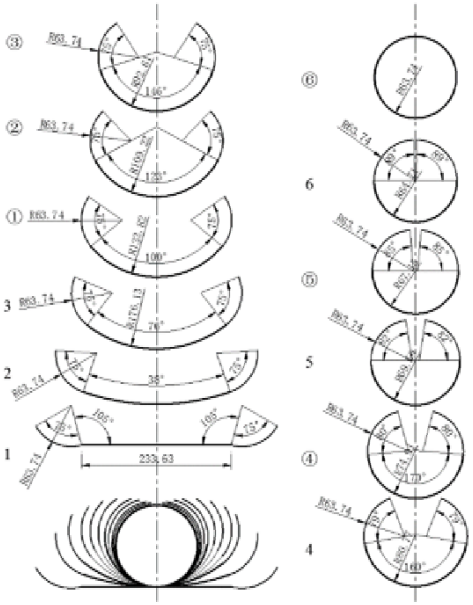
G3: CHS89×3, RHS70×3

G4: CHS50.8×2, RHS40×2

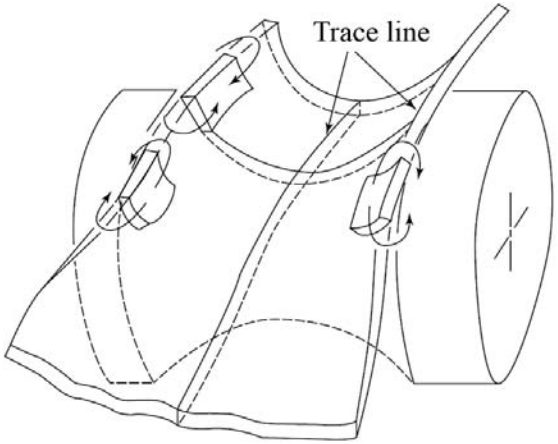
✓ Sponsored by JiangSu Dongge Stainless Steel Ware Co. Ltd.

2. Introduction to cold rolling process

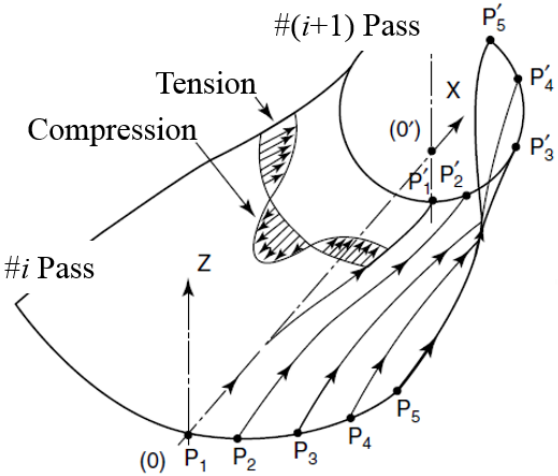
■Plastic deformation in Cold rolling



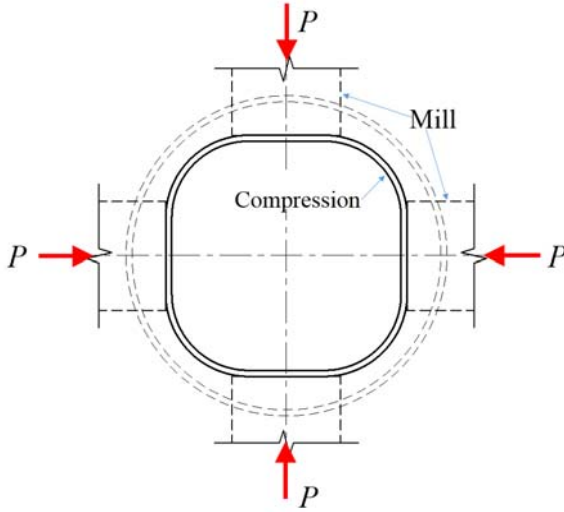
Transverse bending



Longitudinal bending



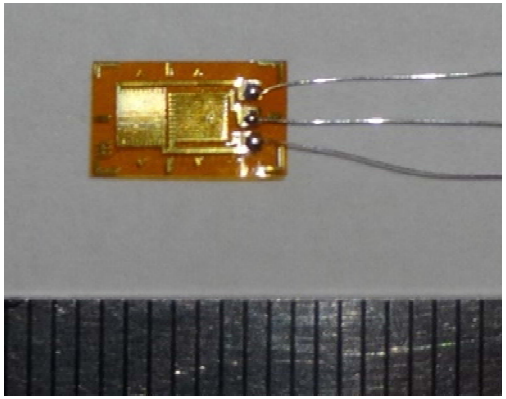
Longitudinal tension and compression

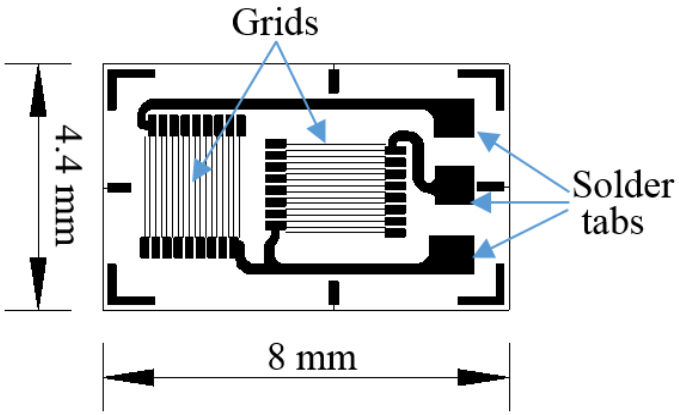


Transverse compression

3. Residual stress measurement and distribution model

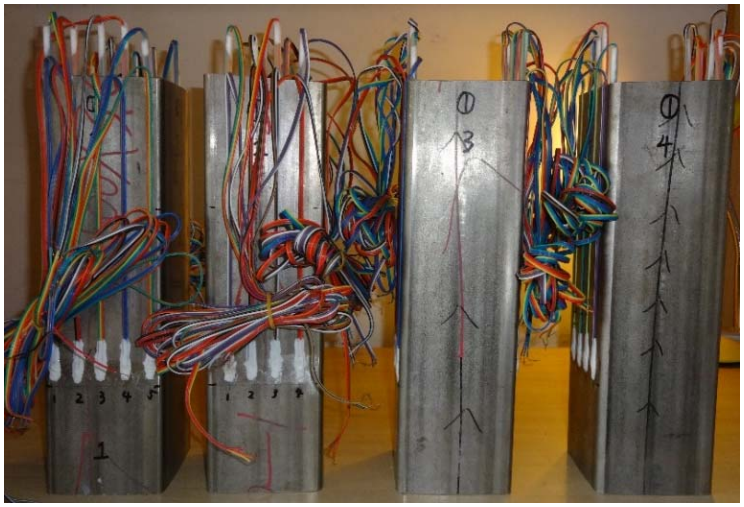
- Residual stress measurement
  - **Type of stress:** Longitudinal and transverse, bending and membrane stresses
  - **Main method:** Modified Sectioning method
  - **Validation method:** *Rise method* and *Splitting method*
- **T rosettes** with two measuring grids, offset by 90 degree

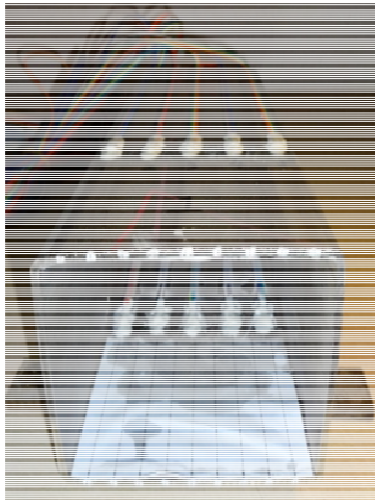


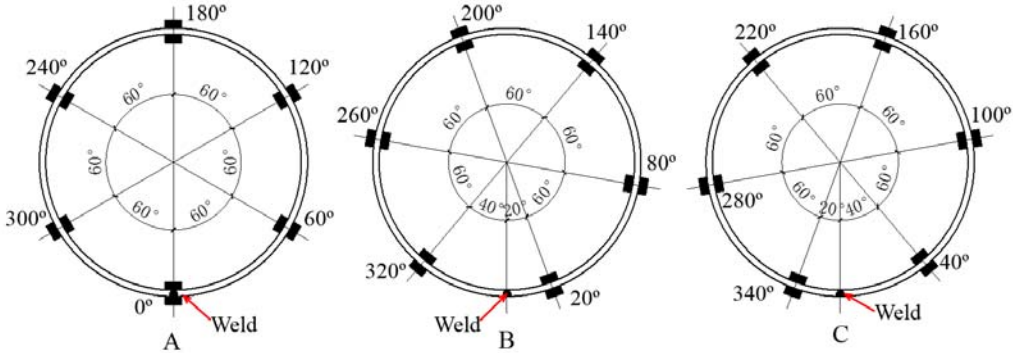


3. Residual stress measureme

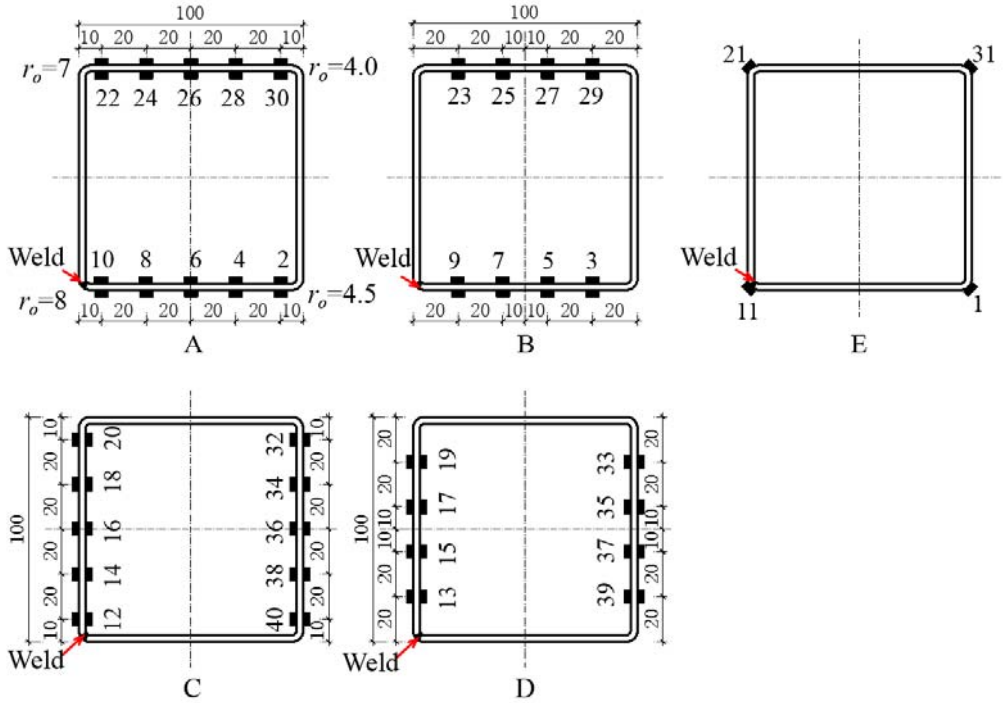
■Test specimens







CHS127×3 measure points



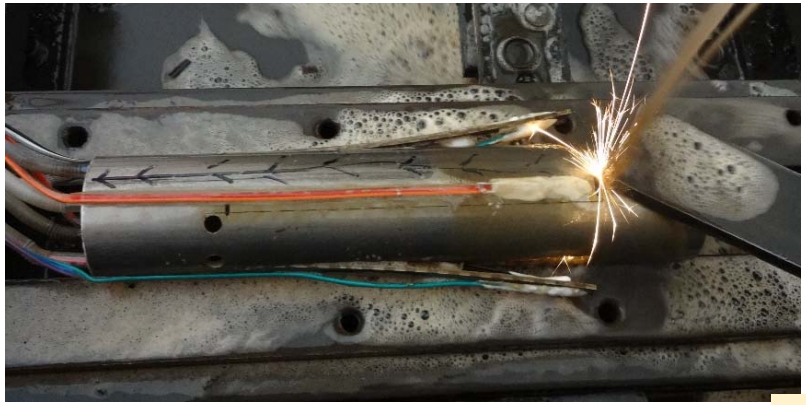
RHS100×3 measure points

- ✓ Strain gauges were passed on outer and inner surfaces.
- ✓ No strain gauge was passed on inner surface of corners.
- ✓ The width of the strip were about 8mm~10mm.
- ✓ Length of specimens: 150+2H.
- ✓ Several specimens were used to minimize the interactive effect.

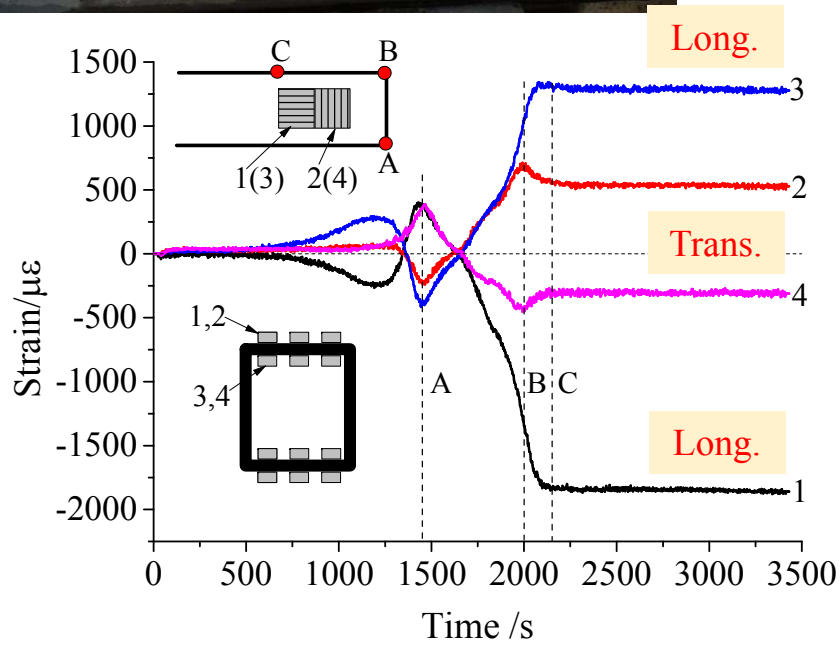
3. Residual stress measurement and distribution model

Flat face of RHS

Corner of RHS



CHS



- Cutting operation was performed using a WEDM.
- Times history strain data were recorded by TDS303.

Results:

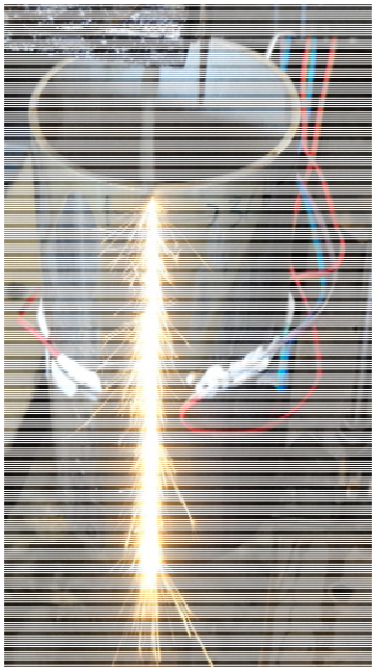
- ✓ All the strips show outward bending.
- ✓ The strain times history curves show plane strain state.

3. Residual stress measurement and distribution model

- Totally, 160 points were measured.

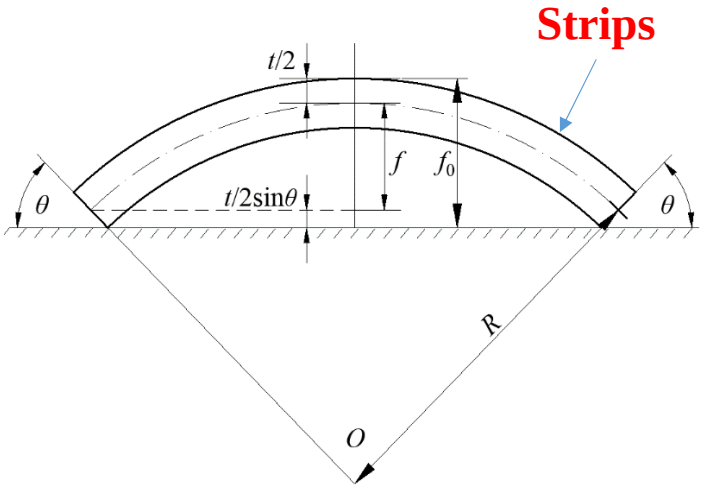
Test results were validated using Methods with clear physical meanings.

All specimens



Splitting method

✓ To verify transverse bending residual stresses

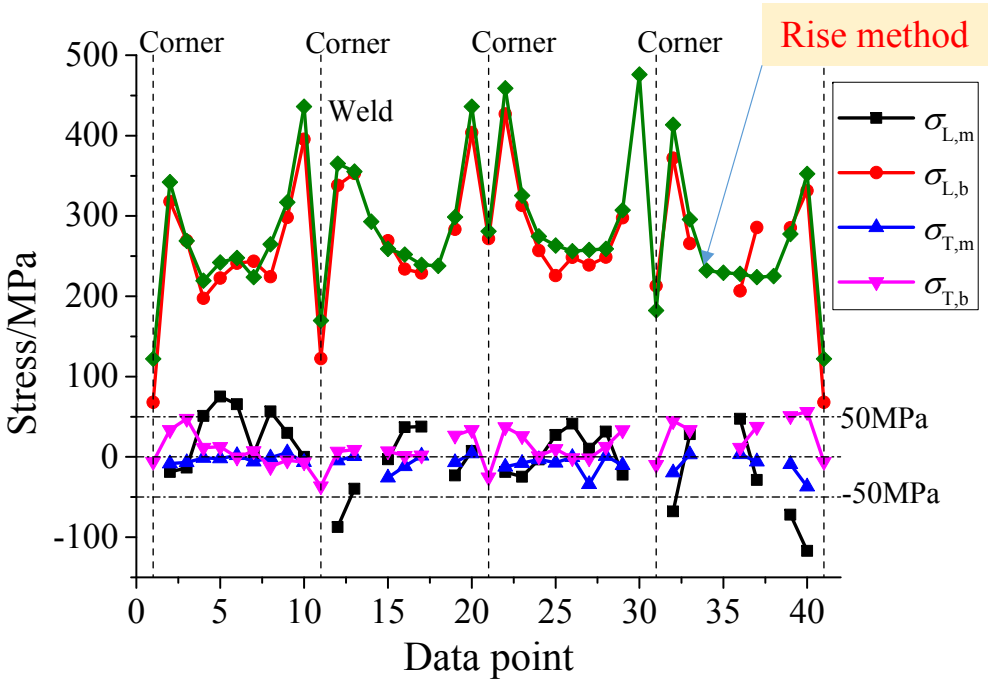


Rise method

✓ To verify Longitudinal bending residual stresses

3. Residual stress measurement and distribution model

Test results-**RHS**

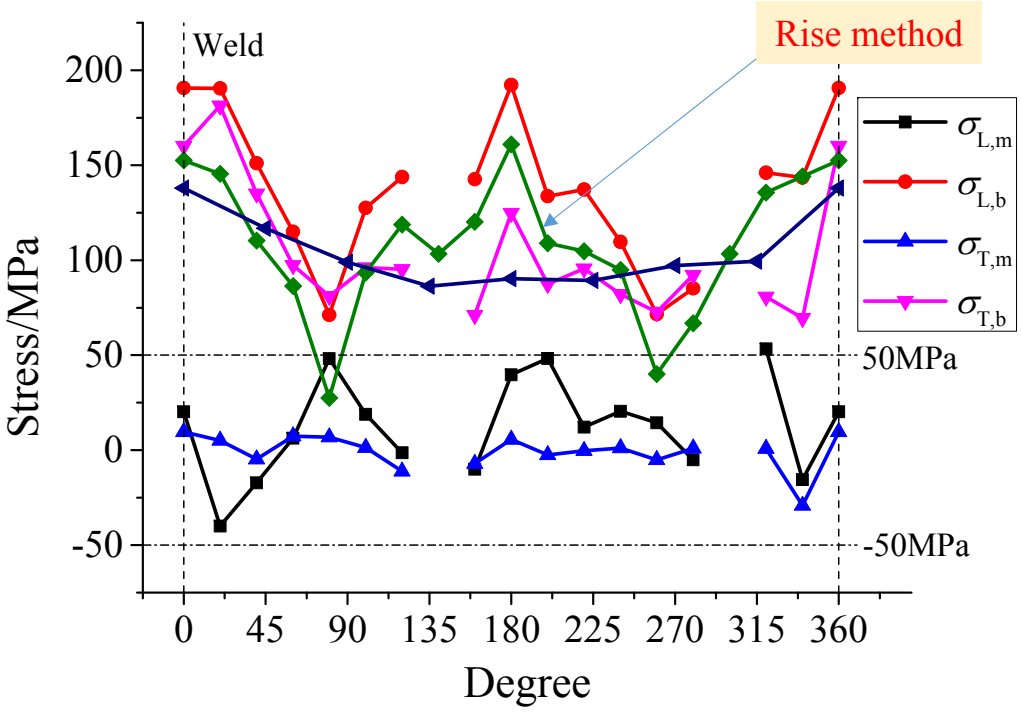


RHS100×3

- ✓ $\sigma_{L,b}$ Longitudinal bending residual stresses were the dominant component stress. Others were less than 50MPa.
- ✓ Longitudinal bending residual stresses in the corner region were less than the nearby flat region.
- ✓ No clear difference was shown between regions around the weld and other regions.

3. Residual stress measurement and distribution model

Test results-**CHS**

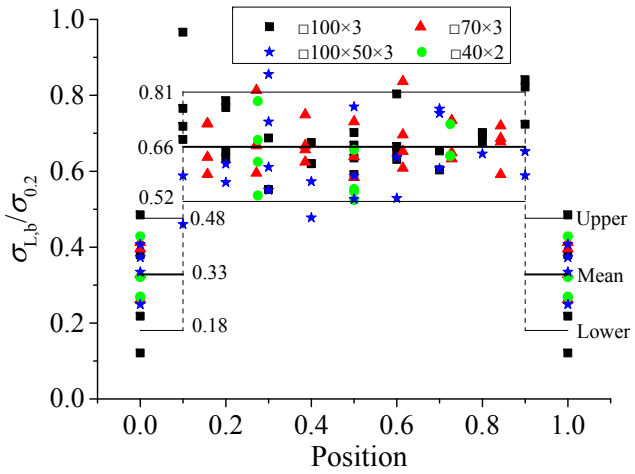


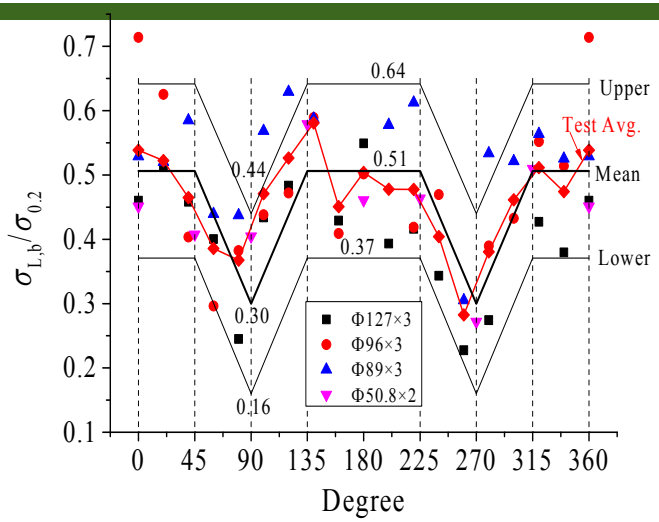
CHS127×3

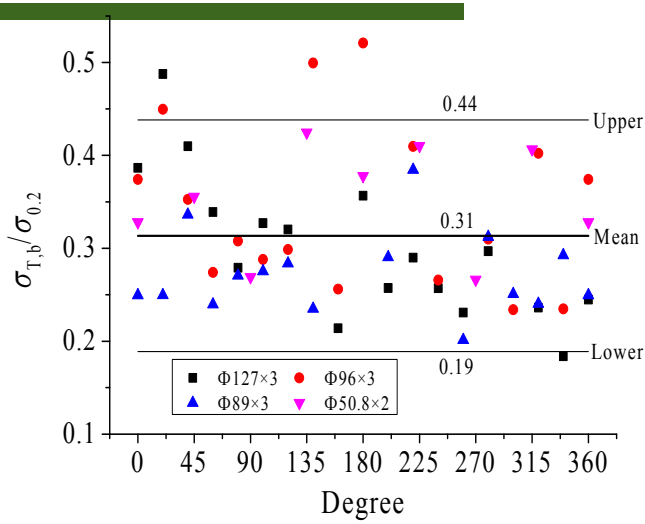
- ✓ $\sigma_{L,b}, \sigma_{T,b}$ Longitudinal and transverse bending residual stresses were the dominant component stress. Others were less than 50MPa.
- ✓ Longitudinal bending residual stresses show **a 'W' type** distribution pattern.
- ✓ The transverse bending residual stresses were approximately evenly distributed along the cross section.

3. Residual stress measurement and distribution model

◆ Test results

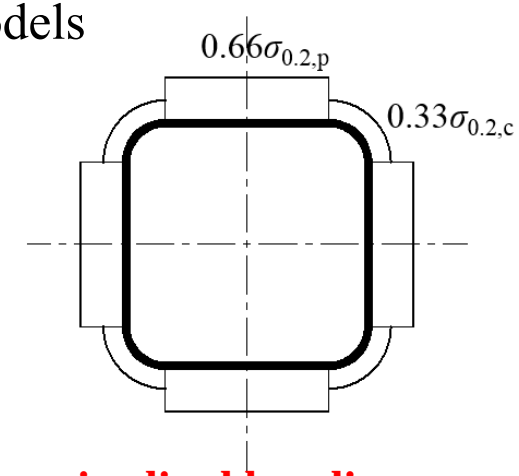




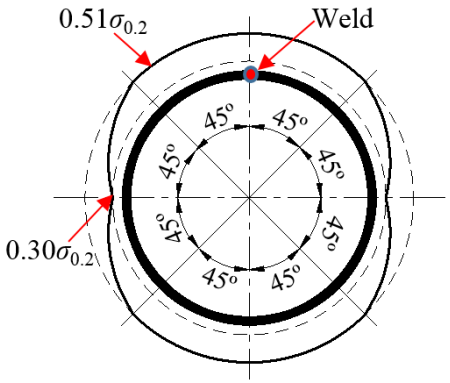


◆ Distribution models

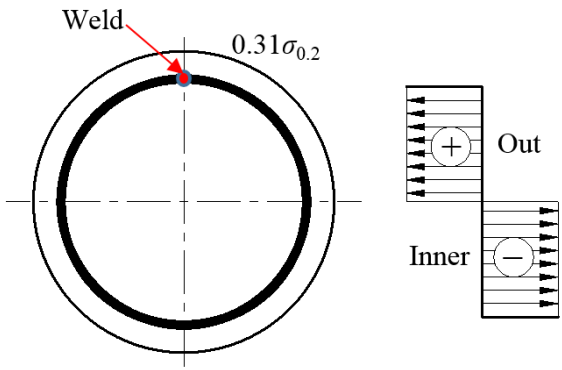
✓ Test results normalized by yield stress.



Longitudinal bending stress RHS



Longitudinal bending stress CHS

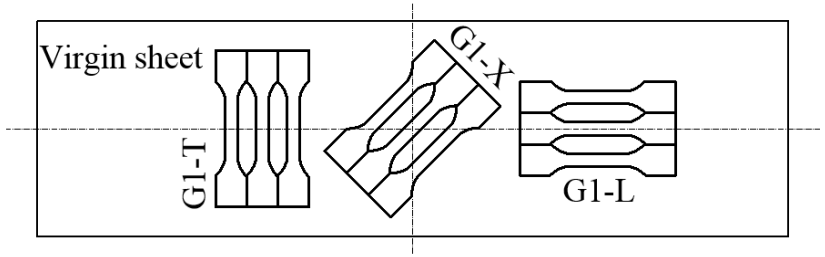


Transverse bending stress CHS

4. Material tensile test and strength enhancement model

- Material tensile test: obtain all the material parameters
- Test coupons:
  - Source: Virgin plates and strips from residual stress test
  - Totally: 36+94 =130 coupons
- Standard: Chinese standard GB/T 228.1-2010

✓ Two strain gauges
✓ Extensometer



Virgin sheet

Strips from residual stress test

Test rig

4. Material tensile test and strength enhancement model

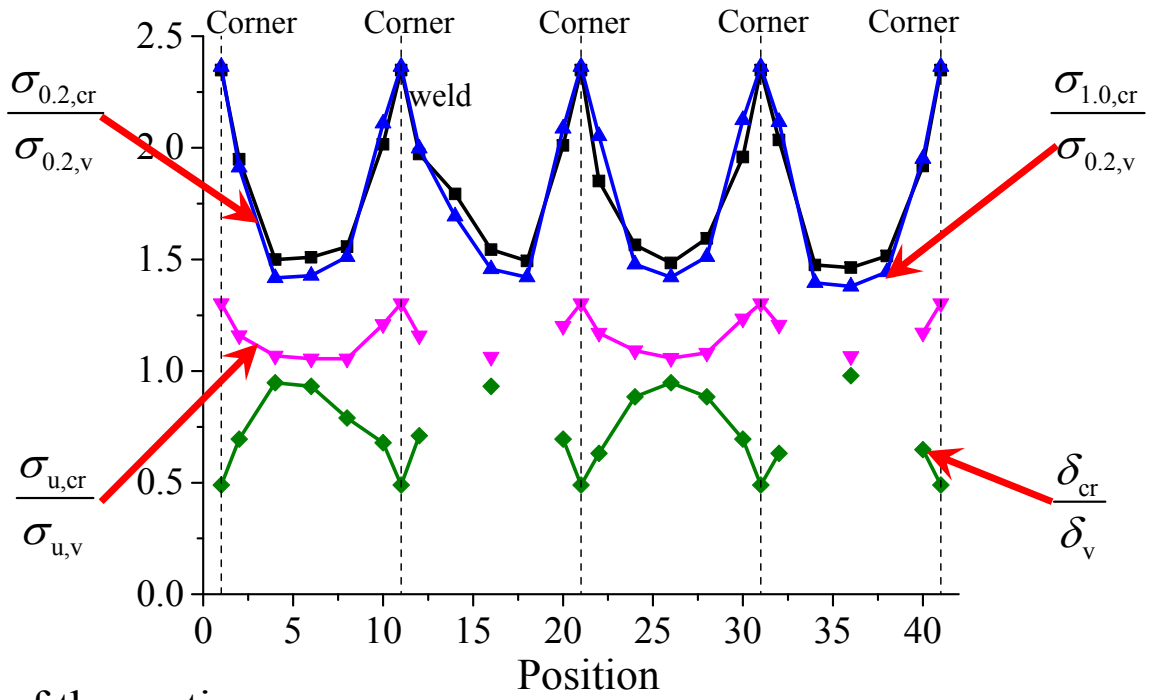
Test result-**RHS**

- Normalized by material properties of virgin sheet.

Virgin sheet properties

Coupons	E_0/MPa	$\sigma_{0.2}$/MPa	σ_u/MPa	n	δ
G4-Long	187566	231.78	627.61	4.97	0.63
G4-Diag	190186	239.60	619.21	5.24	0.65
G4-Trans	205396	247.94	647.70	7.91	0.62

RHS100×3mm



- ✓ Material parameters varies along the flat face of the section.
- ✓ Yield stress, Ultimate tensile stress increases continually from center of face face to the corners.
- ✓ Percentage elongation after fracture decreases as Ultimate tensile stress increases.

4. Material tensile test and strength enhancement model

Test result-CHS

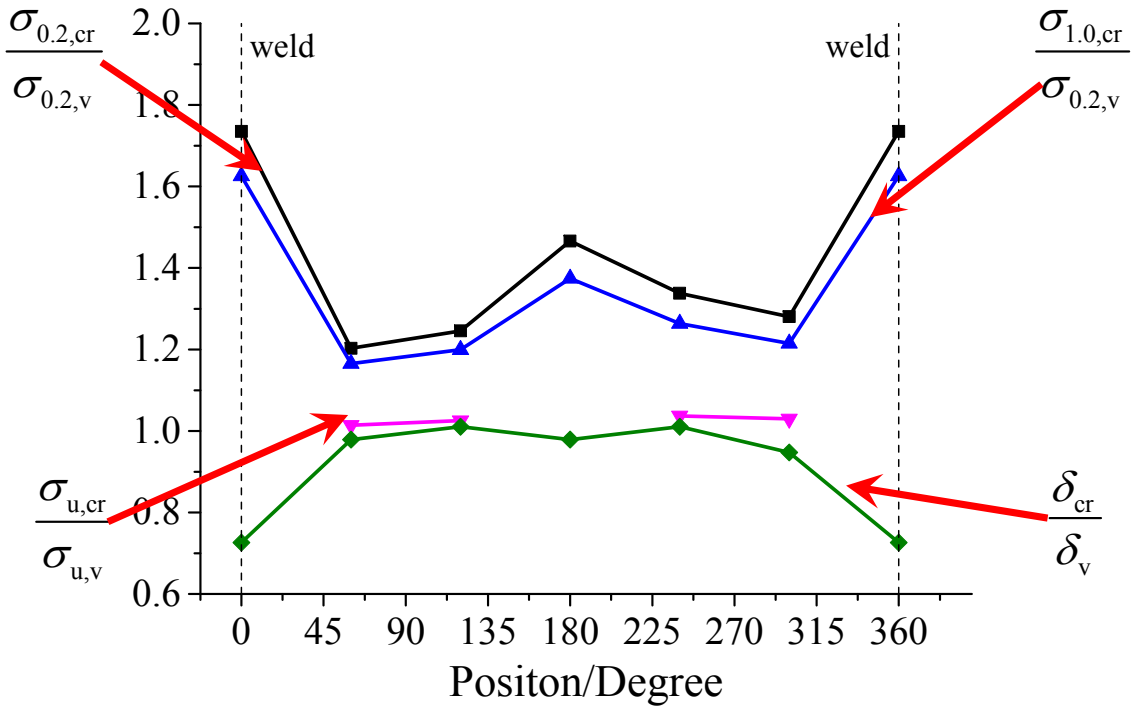
- Normalized by material properties of virgin sheet.

Virgin sheet properties

Coupons	E_0/MPa	$\sigma_{0.2}$/MPa	σ_u/MPa	n	δ
G4-Long	187566	231.78	627.61	4.97	0.63
G4-Diag	190186	239.60	619.21	5.24	0.65
G4-Trans	205396	247.94	647.70	7.91	0.62

Share the same virgin material parameters with RHS100×3mm

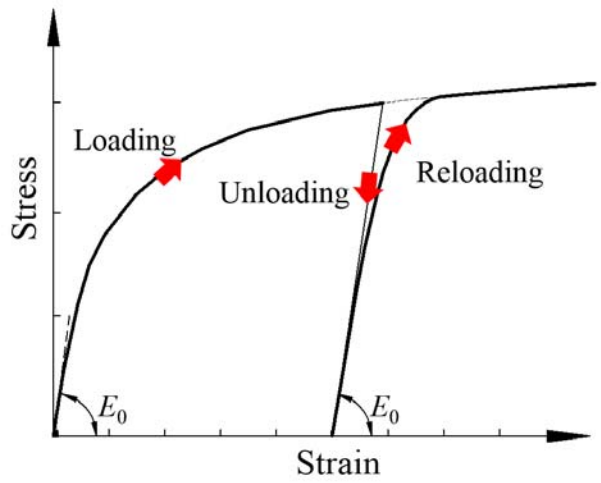
CHS127×3mm



- ✓ Yield stress of weld was much higher than that of other coupons, while the elongation percentage was lower than that of other coupons.
- ✓ For coupons except welds, yield stress increased by 20%, ultimate stress did not change a lot.

4. Material tensile test and strength enhancement model

- Strength enhancement model
- **Target:** To generate full-range material stress-strain curves for cold formed sections based on *virgin material parameters* and *plastic strain*.
- **Step:**
  - (1)Select or develop a simple material model;
  - (2)determine maximum plastic strain;
  - (3)Determine *Equivalent strain* for each parameters using isotropic hardening and data fitting method.



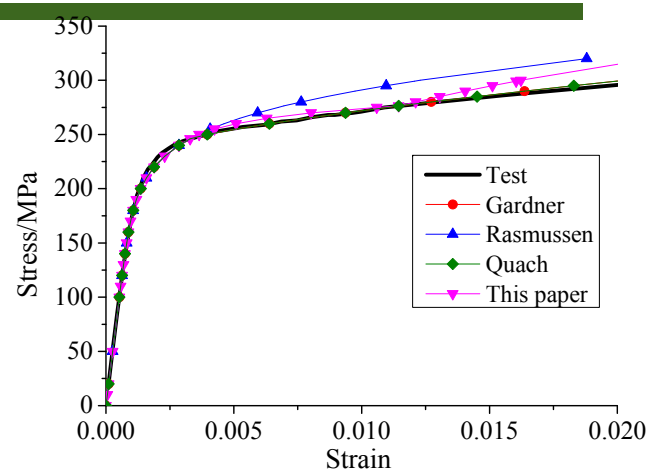
Step 1: Simple material model

Material model-**Simple three-stage model**

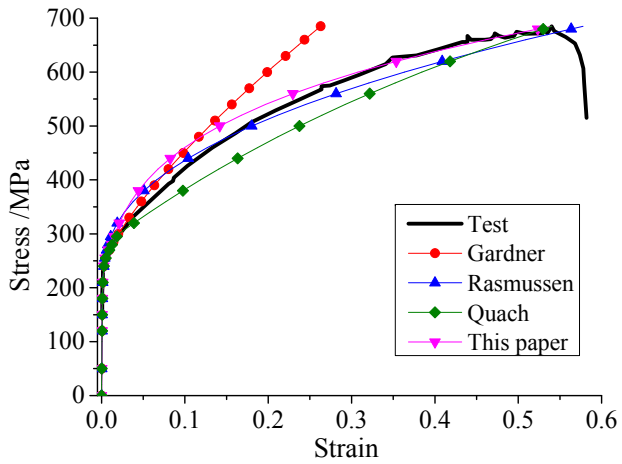
- Six parameters: E_0, $\sigma_{0.2}$, n, $\sigma_{1.0}$, σ_u and ε_u

$$\varepsilon=\begin{cases}\dfrac{\sigma}{E_0}+0.002\left(\dfrac{\sigma}{\sigma_{0.2}}\right)^{n} & 0\le\sigma\le\sigma_{0.2}\\[2ex] \dfrac{\sigma}{E_0}+0.002\left(\dfrac{\sigma}{\sigma_{0.2}}\right)^{n_2} & \sigma_{0.2}<\sigma\le\sigma_{1.0}\\[2ex] \left(\dfrac{\sigma}{p}\right)^{q} & \sigma_{1.0}<\sigma\le\sigma_{u}\end{cases}$$

- ✓ Similar accuracy with the current popular models
- ✓ Simple in formula, easy to get all parameters



Initial stage



Full range

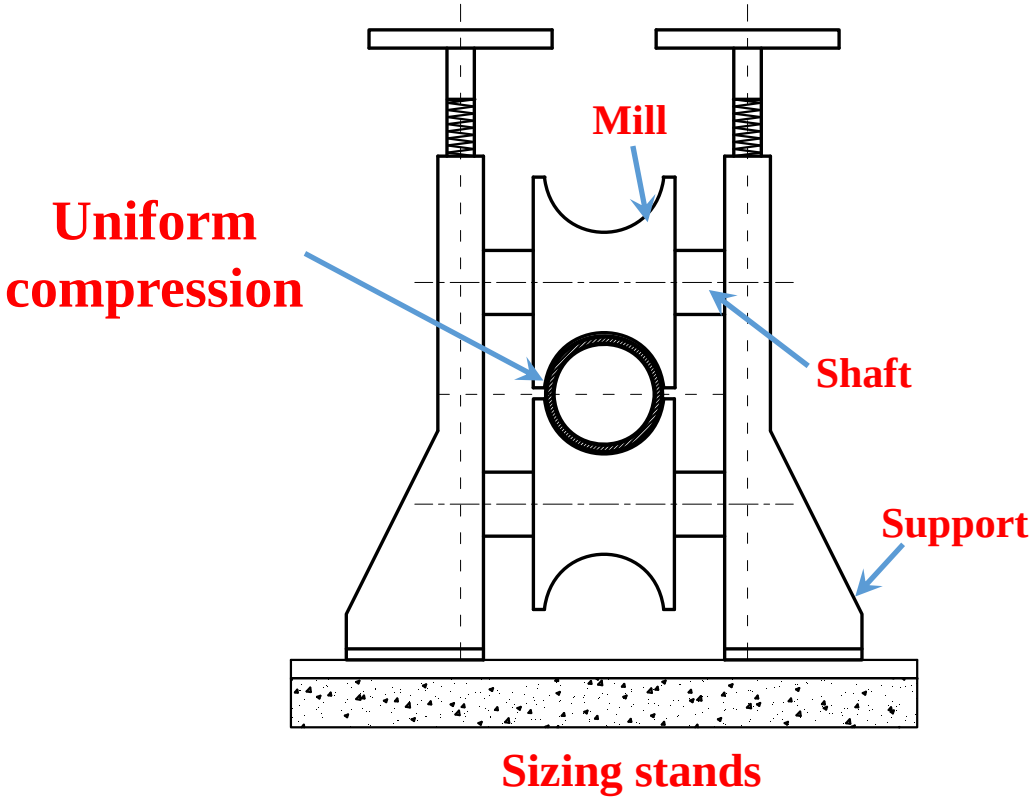
Step 2: Maximum plastic strain

Forming a CHS:

- Bending a sheet to an arc with radius R
- Uniform compression (Diameter reducing rate)

Maximum strain $\frac{t}{2R}$

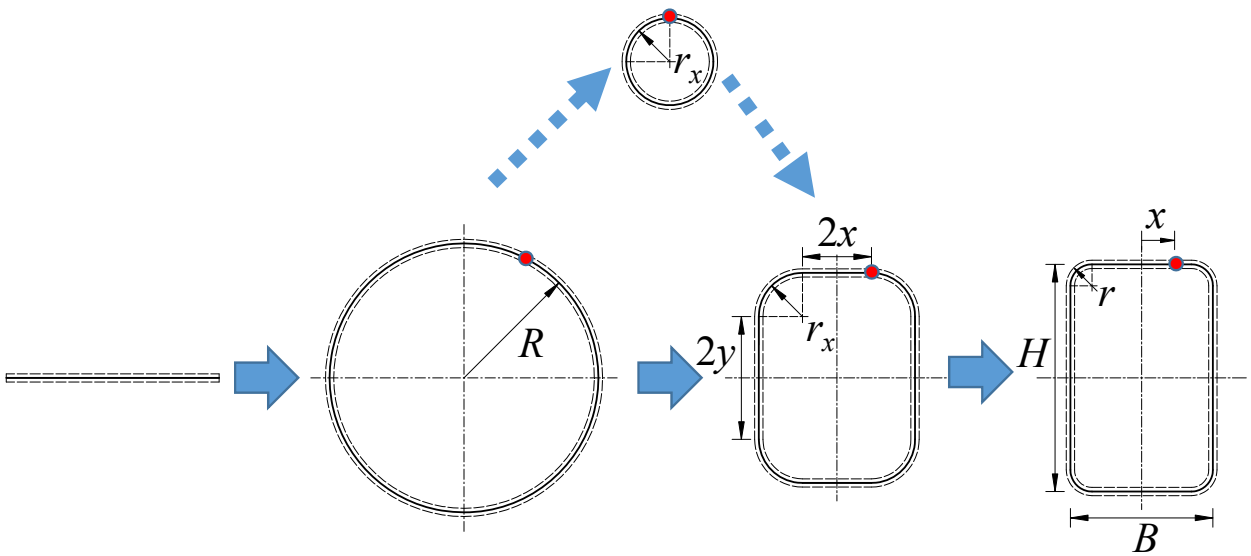
About 1%



Step 2: Maximum plastic strain

Forming a RHS:

- **Bending** a sheet to an arc with radius r_x and then **flatting** it.
- Assumption: plastic strain in flatting **equals** to that in bending process.



Sheet **CHS** **CHS to RHS** **RHS**

$$\begin{cases} r_x = \dfrac{2\pi R - 4\left(1+\dfrac{H}{B}\right)x}{2\pi} \\ \varepsilon_{\max} = \dfrac{t}{2r_x} + \dfrac{t}{2r_x} \end{cases}$$

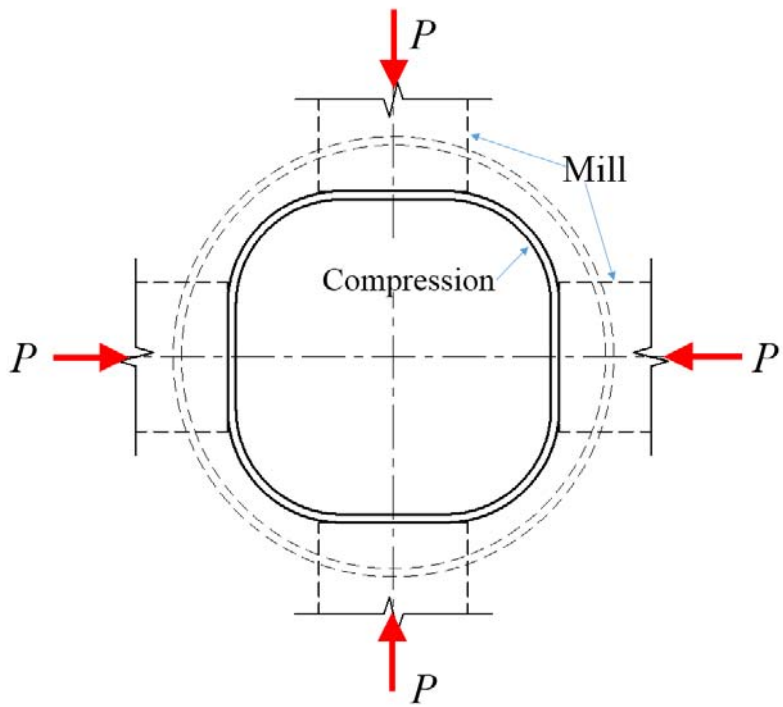
Maximum strain

Similar to *Rossi B., Afshan S., Gardner L. Strength enhancements in cold-formed structural sections —Part II: Predictive models.*

Step 2: Maximum plastic strain

Forming a RHS:

- **Bending** a sheet to an arc with radius r_x and then **flatting** it.
- Assumption: plastic strain in flatting **equals** to that in bending process.
- Transverse compression: **About 2%.**



Step 3: Determine equivalent strain

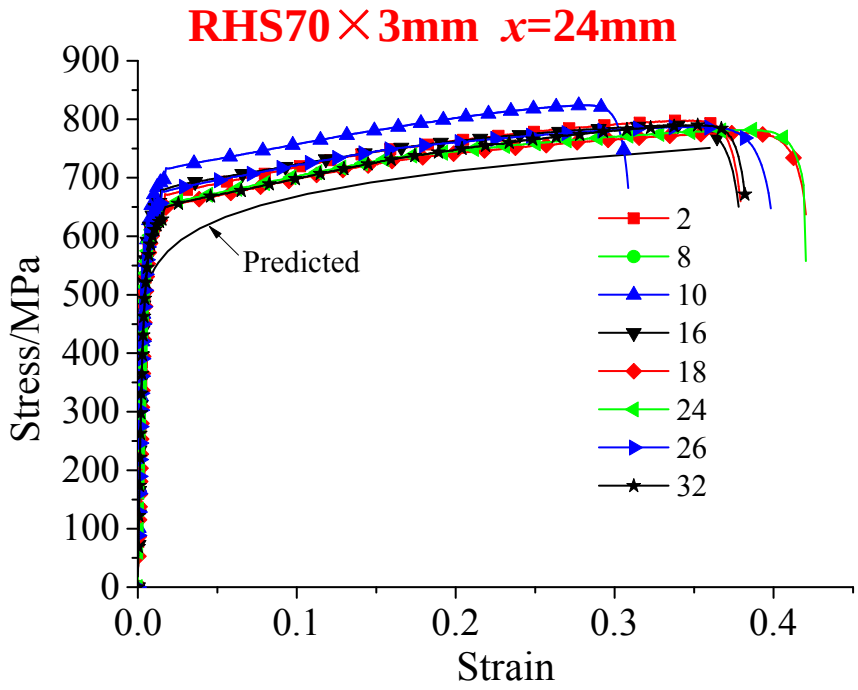
	$\sigma_{0.2}$	$\sigma_{1.0}$	σ_u ε_u	n
CHS	$\begin{cases} \sigma_{0.2,\mathrm{cr,cir}} = \sigma_{0.2,\mathrm{v}}\left(1+\alpha\cdot\varepsilon_{\mathrm{eq}}^{0.5}\right) \\ \alpha = \dfrac{1.5\left(\dfrac{q}{q+1}\sigma_{\mathrm{u,v}} - \sigma_{0.2,v}\right)}{\sigma_{0.2,v}\cdot\sqrt{\varepsilon_{\mathrm{u,v}}}} \\ \varepsilon_{\mathrm{eq}} = \dfrac{1}{2}\dfrac{t}{2R} + 0.01 \end{cases}$	$\begin{cases} \sigma_{1.0,\mathrm{cr,cir}} = p\cdot\sqrt[q]{\varepsilon_{\mathrm{eq}}+\varepsilon_{1.0,\mathrm{v}}}\left(1+0.5\varepsilon_{\mathrm{eq}}^2\right) \\ \varepsilon_{\mathrm{eq}} = \dfrac{3}{4}\dfrac{t}{2R} + 0.01 \end{cases}$	$\begin{cases} \varepsilon_{\mathrm{u,cr,cir}} = e^{\varepsilon_{\mathrm{t,u}}-\varepsilon_{\mathrm{t,eq}}} - 1 \\ \sigma_{\mathrm{u,cr,cir}} = \dfrac{\sigma_{\mathrm{t,u}}}{1+\varepsilon_{\mathrm{u,cr,cir}}} \\ \varepsilon_{\mathrm{t,eq}} = \dfrac{3}{4}\ln\left(1+\dfrac{t}{2R}\right) \end{cases}$	$n_{\mathrm{cr,cir}} = 0.45 n_{1,\mathrm{cr,cir}} = 0.45 * \dfrac{\ln(5)}{\ln\left(\sigma_{1.0,\mathrm{cr,cir}}/\sigma_{0.2,\mathrm{cr,cir}}\right)}$
RHS Flat region	$\begin{cases} \sigma_{0.2,\mathrm{cr,f}} = \sigma_{0.2,\mathrm{v}}\left(1+\alpha\cdot\varepsilon_{\mathrm{eq}}^{0.5}\right) \\ \alpha = \dfrac{1.5\left(\dfrac{q}{q+1}\sigma_{\mathrm{u,v}} - \sigma_{0.2,v}\right)}{\sigma_{0.2,v}\cdot\sqrt{\varepsilon_{\mathrm{u,v}}}} \\ \varepsilon_{\mathrm{eq}} = \dfrac{1}{2}\dfrac{t}{r_x} + 0.03 \\ r_{\mathrm{x}} = \dfrac{2\pi R - 4\left(1+\dfrac{H}{B}\right)x}{2\pi} \end{cases}$	$\begin{cases} \sigma_{1.0,\mathrm{cr,f}} = p\cdot\sqrt[q]{\varepsilon_{\mathrm{eq}}+\varepsilon_{1.0,\mathrm{v}}}\left(1+0.5\varepsilon_{\mathrm{eq}}^2\right) \\ \varepsilon_{\mathrm{eq}} = \dfrac{3}{4}\dfrac{t}{r_{\mathrm{x}}} + 0.03 \end{cases}$	$\begin{cases} \varepsilon_{\mathrm{u,cr,f}} = e^{\varepsilon_{\mathrm{t,u}}-\varepsilon_{\mathrm{t,eq}}} - 1 \\ \sigma_{\mathrm{u,cr,f}} = \dfrac{\sigma_{\mathrm{t,u}}}{1+\varepsilon_{\mathrm{u,cr,f}}} \\ \varepsilon_{\mathrm{t,eq}} = \dfrac{3}{4}\ln\left(1+\dfrac{t}{r_{\mathrm{x}}}\right) \end{cases}$	$n_{\mathrm{cr,f}} = 0.45 n_{1,\mathrm{cr,f}} = 0.45 * \dfrac{\ln(5)}{\ln\left(\sigma_{1.0,\mathrm{cr,f}}/\sigma_{0.2,\mathrm{cr,f}}\right)}$
	Isotropic hardening	**Isotropic hardening**	**Based on test data**	**Based on test data**

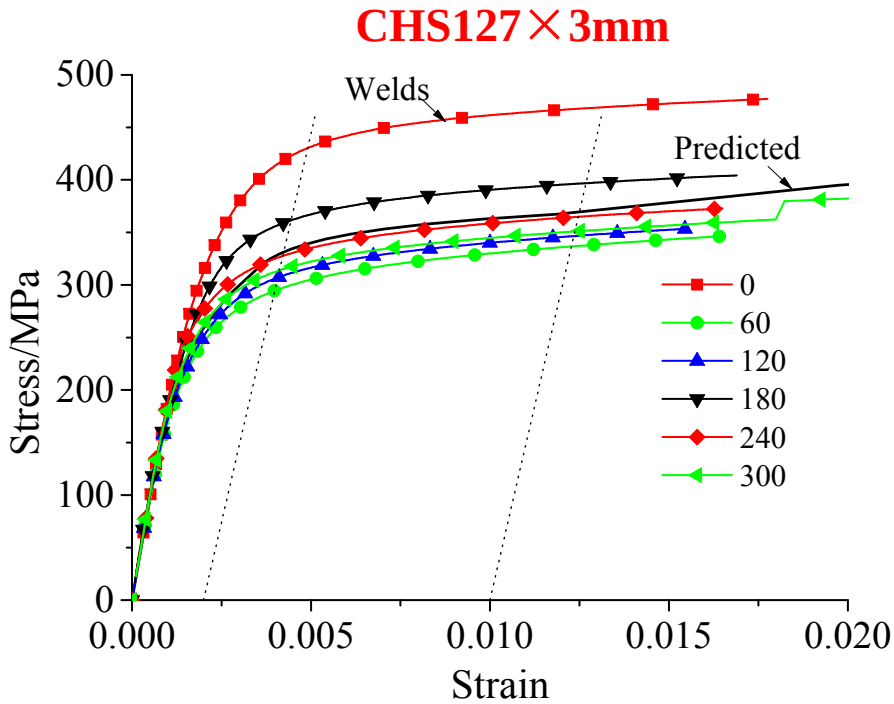
Equivalent strain

Strain hardening exponent in first stage is about 0.45 times that of the second stage.

4. Material tensile test and strength enhancement model

Comparison: with test data in this paper





- ✓ The predicted stress-strain curve can represent the test stress-strain curve with an acceptable accuracy.
- ✓ Full range stress-strain curve

5. Conclusions

- **Residual stresses: (1)** Longitudinal bending residual stresses and transverse bending residual stresses were the dominate types of residual stress. **(2)** Outer surface of the section was in tension. **(3)** The maximum residual stress was lower than yield stress.
- **Material properties: (1)** Material yield stress increased a lot due to plastic strain in cold rolling. **(2)** Degree of incensement depends on the plastic strain. **(3)** The proposed model could generate full range stress-strain curves of cold rolled sections based on virgin sheet material properties and equivalent strain.

Thank you for your attention!