Strength and Ductility of Corner Materials in Cold-Formed Stainless Steel Sections

By W.M. Quach, & P. Qiu

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Cold-Work Effect on Stainless Steel Corner Mechanical Properties

Experimental stress-strain curves
(e.g., grade 304, inner corner radius $r_i = 4\text{mm}$, thickness $t = 2\text{mm}$)
Existing Empirical Models for Stainless Steel Corner Strength

Existing empirical models for stainless steels (Van den Berg & Van der Merwe 1992, Ashraf et al. 2005, AS/NZS4673 2001) were based on Karren’s Methodology (1967) for carbon steels:

\[
\sigma_{0.2,c} = B_c \sigma_{0.2,v}^{m} \left( \frac{r_i}{t} \right)
\]

\[
\sigma_{0.2,c} = C_1 \sigma_{u,v}^{c_2} \left( \frac{r_i}{t} \right)
\]

Enhanced Ultimate Strength by Linear Eq. (Ashraf et al. 2005):

\[
\sigma_{u,c} = 0.75 \sigma_{0.2,c} \left( \frac{\sigma_{u,v}}{\sigma_{0.2,v}} \right)
\]
Objective

- **Advanced Numerical Approach**:
  To determine the *enhanced strength*, *reduced ductility* & *full stress-strain behaviour* of corner materials cold-formed stainless steel sections theoretically & numerically.
Necking of Thin-Walled Materials under Uniaxial Tension

Localized necking

Diffuse necking

σ

Nominal stress

Post-Ultimate Stress-strain behaviour

(Onset of diffuse necking)

(Onset of localized necking)

(Fracture)

Approximation:
Fracture strain ≈ strain at Point L

Flat coupon

Corner coupon

Very rapid

(Reproduced from Zhang et al. 1999)
Advanced Numerical Approach – Corner Mechanical Behaviour

Modified Weighted-Average Method (MWA)

Post-ultimate behaviour

U (Necking)

F (Fracture)

VIRGIN material

Compound True Stress-Plastic Strain Curve

FE prediction of Residual Stresses & Equivalent Plastic Strains in Corners

Numerical Corner Coupon Test

FE model for half gauge length

CORNER material

Test results

0 1000
Nominal stress (MPa)

Nominal strain

Initial notches at the mid-length section

Applied displacement
Verification of Proposed Approach – Experimental Study

- Two testing methods [Single Corner (SC) test, Twin Corner (TC) test]
- Totally 16 SC tests + 8 TC tests of press-braked corners
- Two batches of tests.
- Two grades (304, 316L) for each batch.
- Two inner corner radii ($r_i = 4$ mm, 6 mm); thickness $t = 2$ mm.
- Flat coupon tests for mechanical properties of virgin sheets: Longitudinal (L), Transverse (T) and Diagonal (D) directions.
Outline

- Introduction & Objective
- Advanced Numerical Approach -- Corner Mechanical Behaviour
  - Modified Weighted-Average Method – Compound true stress-plastic strain curve
  - FE Prediction of Residual Stresses in Corners
  - Numerical Corner Coupon tests
- Results & Comparisons
- Summary & Conclusions
Modified Weighted-Average Method

- Weighted-Average Method (Ling 1996):

\[ \sigma_t = \left( \sigma_{t,u} \right) \left[ w \left( 1 + \varepsilon_{tp,f} - \varepsilon_{tp,u} \right) + \left( 1 - w \right) \frac{\varepsilon_{tp,f}}{\varepsilon_{tp,u}} \right] \]

- Modified Weighted-Average Method (Present study):

\[ \varepsilon_{tp} = \left( \frac{w}{1 + G/F} \right) \left( 1 + \varepsilon_{tp,f} - \varepsilon_{tp,u} \right) + \left( \frac{1 - w}{1 + G/F} \right) \frac{\varepsilon_{tp,f}}{\varepsilon_{tp,u}} - (1 - w) \frac{\varepsilon_{tp,f}}{\varepsilon_{tp,u}} \]

Consider the effect of Material Anisotropy

Anisotropic metal:

\[ \bar{\sigma} = \sqrt{\frac{3}{2}} \left( \frac{F + G}{F + G + H} \right) \sigma_t, \quad \bar{\varepsilon}_p = \sqrt{\frac{2}{3}} \left( \frac{F + G + H}{F + G} \right) \varepsilon_{tp} \]
Modified Weighted-Average Method

\[
\left( \frac{w}{1 + G/F} \right) \left( 1 + \varepsilon_{tp,f} - \varepsilon_{tp,u} \right) + \left( \frac{1 - w}{1 + G/F} \right) \left( \frac{\varepsilon_{tp,f}}{\varepsilon_{tp,u}} \right)^{\varepsilon_{tp,u}^{-1}} - (1 - w) \left( \frac{\varepsilon_{tp,f}}{\varepsilon_{tp,u}} \right) - w = 0
\]

**Onset of diffuse necking**

**Weight constant**

\[ w = ? \]

**True plastic strain at fracture**

**Lower bound:** \( \varepsilon_{tp,f} = (1 + G/F) \varepsilon_{tp,u} \) at \( w = 0 \)

**Upper bound:** \( \varepsilon_{tp,f} = \varepsilon_{tp,u} + G/F \) at \( w = 1 \)
Modified Weighted-Average Method – Determination of Weight Constant & $\varepsilon_{tp,f}$

**True plastic strain at fracture** $\varepsilon_{tp,f}$

**Trial weight constant** $w$

**Post-ultimate behaviour**

- U (Necking)
- F (Fracture)

**Initial notches**

**FE simulation of Flat Coupon Test**

**FE model for half gauge length**

**(Inverse technique)**

- No
- Yes

**FE prediction** ≈ Test result

**Predicted** $w, \varepsilon_{tp,f}$, True stress-plastic strain curve

**Nominal stress (MPa)**

- Test results
- F.E.A.

**Nominal strain**

- VIRGIN material
- FE predicted curve vs. Test curve
Weight Constants for Virgin (Flat) materials

Nominal stress (MPa) vs. Nominal strain

Grade 316L, First Batch
(Specimen FB-316L-LT)
- Test results
- F.E.A. (w = 0.375)

Grade 304, Second Batch
(Specimen SB-304-LT)
- Test results
- F.E.A. (w = 0.5)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Weight constant, $w$</th>
<th>True plastic strain $\varepsilon_{tp,f}$ at fracture</th>
<th>Percentage elongation after fracture</th>
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<tr>
<td>FB-304-LT</td>
<td>0.0</td>
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</table>

FB = First batch, SB = Second batch, LT = Longitudinal flat tension specimen.
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FE Predictions of Residual Stresses in Corners

Corner of Grade 304 (Second Batch): Inner radius = 4 mm, Thickness = 2 mm

CPE4R plane strain elements (32 layers)

$\Gamma_i$ (inner radius)

Normalized residual stress $\sigma_x/\sigma_{0.2}$

Normalized distance $y/t$

Outer surface

Inner surface

Normalized residual stress $\sigma_z/\sigma_{0.2}$

Normalized distance $y/t$

Outer surface

Inner surface

Equivalent plastic strain

Reference node

Fixed end

$r_i$ (inner radius)
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FE Model for Corner Coupons

Symmetrical boundary conditions at the mid-length section

Initial notches on both edges at the mid-length section

Consider:
- Geometrical and material nonlinear
- Material anisotropy

Reference node (Apply prescribed displacement)

S4R shell elements (ABAQUS)
[ with 17 integration points across thickness to allocate residual stresses and equivalent plastic strains ]

\[ \Delta W = 0.002W \]

\[ R = 3W \]
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## Comparisons with Test Results

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<th>Specimen</th>
<th>FEA/Test result</th>
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<td>$\sigma_{u,c}$</td>
<td>$\varepsilon_{50,c}$</td>
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<tr>
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<td>Std. dev.</td>
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$\sigma_{0.2,c} =$ Corner 0.2% proof stress  
$\sigma_{u,c} =$ Corner ultimate strength  
$\varepsilon_{50,c} =$ Percentage elongation after fracture over a 50-mm gauge length of a corner  

* Average value of repeated tests
Comparisons with Test Results

Grade 304 (1st batch) & $r_i/t = 2$

Grade 304 (2nd batch) & $r_i/t = 2$

Grade 316L (1st batch) & $r_i/t = 3$

Grade 304 (2nd batch) & $r_i/t = 3$
### Comparisons with Existing Empirical Models: Corner 0.2% Proof Stress $\sigma_{0.2,c}$

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<td>0.17</td>
<td>0.08</td>
<td>0.09</td>
<td>0.07</td>
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</table>
Existing Empirical Models for Stainless Steel Corner Strength

From Ashraf et al. (2005):

Simple model

$$\sigma_{0.2,c} = 1.881 \sigma_{0.2,v} \left( \frac{r_i}{t} \right)^{0.194}$$

Power model

$$\sigma_{0.2,c} = C_1 \sigma_{u,v} \left( \frac{r_i}{t} \right)^{C_2}$$

Linear Eq.

$$\sigma_{u,c} = 0.75 \left( \frac{\sigma_{u,v}}{\sigma_{0.2,v}} \right) \sigma_{0.2,c}$$

Yield strength and ultimate strength of VIRGIN sheets

Functions of VIRGIN material properties
## Comparisons with Existing Empirical Models: Corner Ultimate Strength $\sigma_{u,c}$

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Summary & Conclusions

- A Modified Weighted-Average (MWA) Method for predicting the Post-ultimate true stress-plastic strain behaviour and fracture strain of virgin stainless steel sheets.

- On the basis of the MWA method, an Advanced Numerical Approach has been proposed for predicting the enhanced strength, reduced ductility, & the complete stress-strain behaviour of corner materials.

- The accuracies of proposed method and approach have been demonstrated by comparing their predictions with test results.

- The proposed method and approach are applicable to various cold-worked materials produced from all types of sheet metals.

- The presented results explain why the ultimate strength of corners can be increased and how the post-ultimate strain-hardening capability of virgin sheets can be utilized through cold forming.
The End of the Presentation

Thank You

Q & A