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

By **W.M. Quach, & P. Qiu**

Speaker: **Dr. W.M. Quach**

University of Macau

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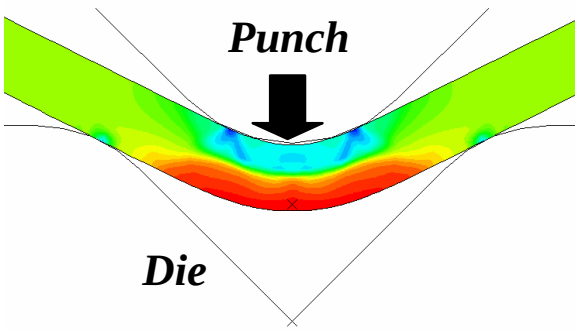
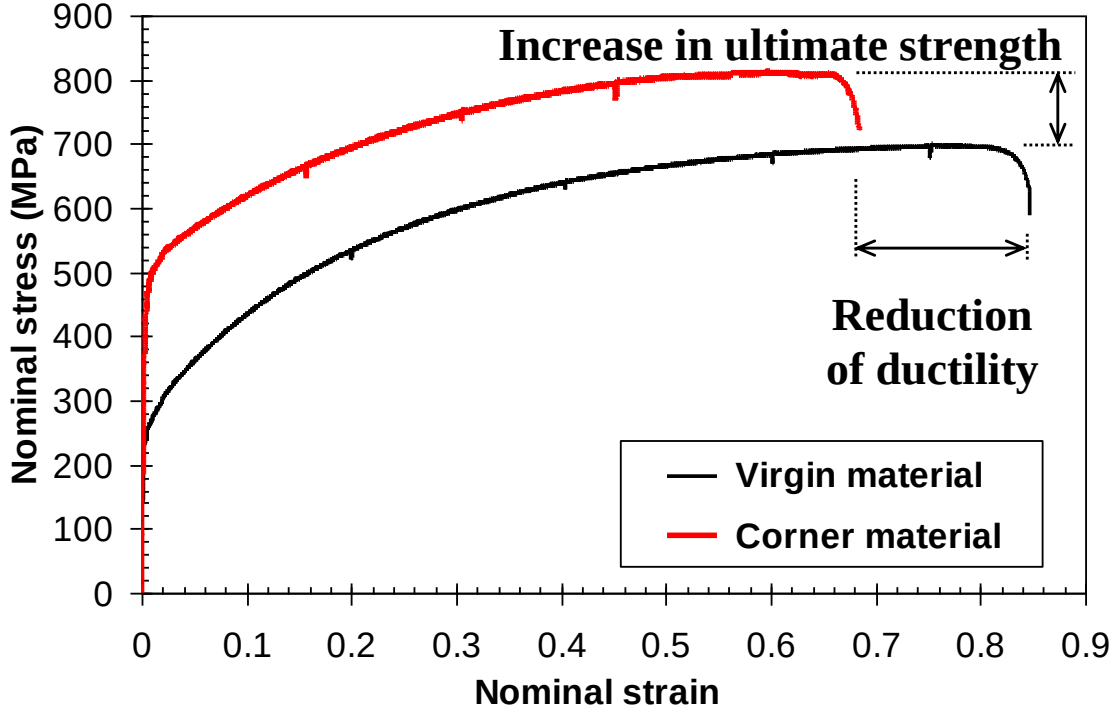
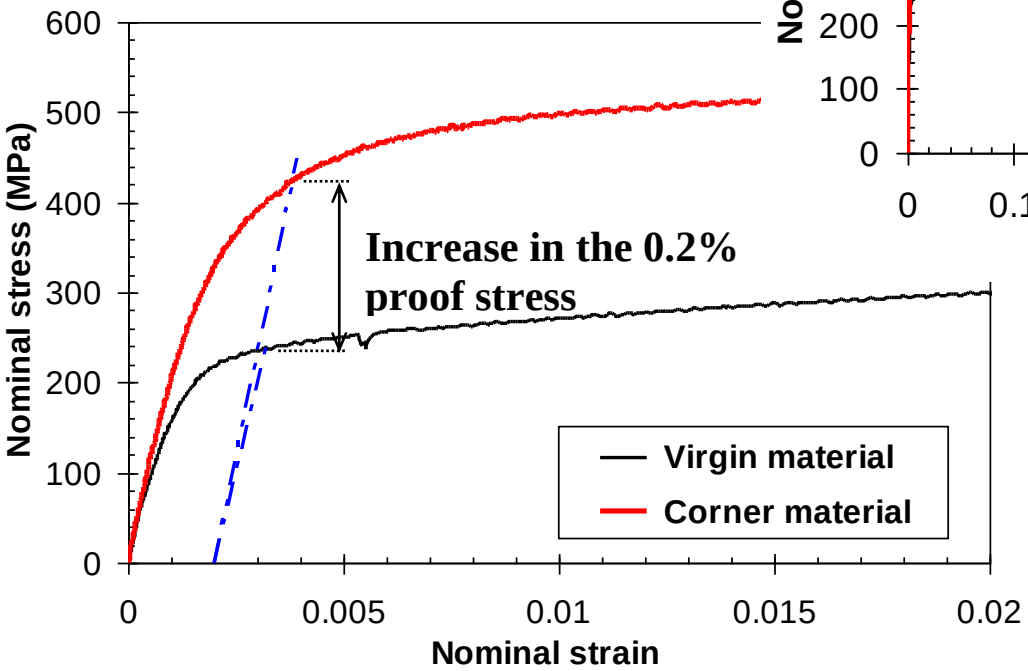
# Cold-Work Effect on Stainless Steel Corner Mechanical Properties




**Experimental stress-strain curves**

**( e.g., grade 304, inner corner radius *ri* = 4mm, thickness *t* = 2 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:**

**Functions of VIRGIN material properties**

**Yield strength and ultimate strength of VIRGIN sheets**

**Enhanced 0.2% Proof Stress:**

$$\sigma_{0.2,c} = B_c \sigma_{0.2,v} \Big/ \left(\frac{r_i}{t}\right)^m$$

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

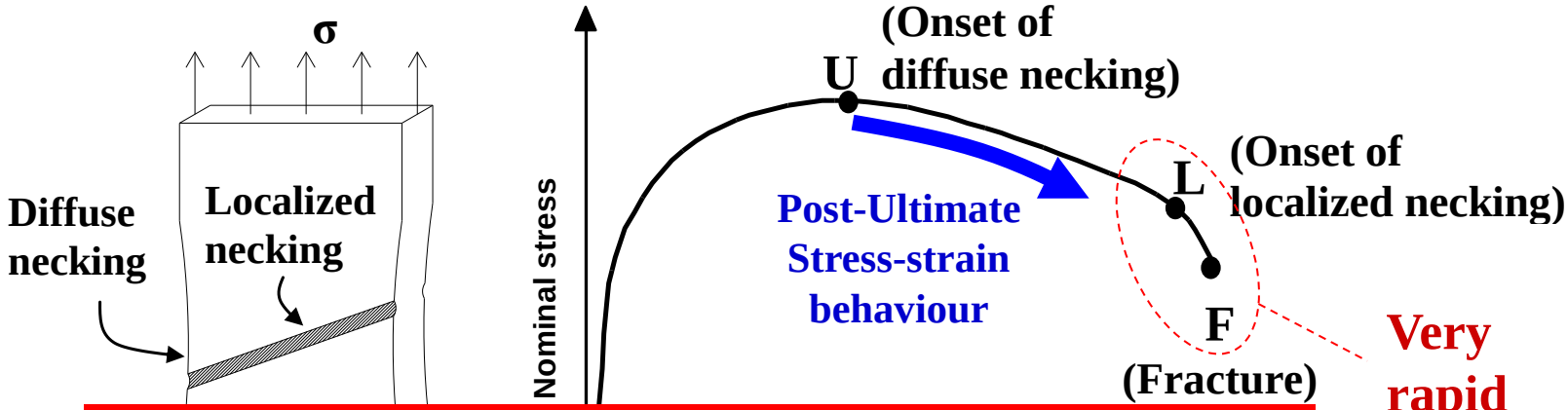
**Enhanced Ultimate Strength by *Linear Eq.* (Ashraf et al. 2005):**

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

# 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.**

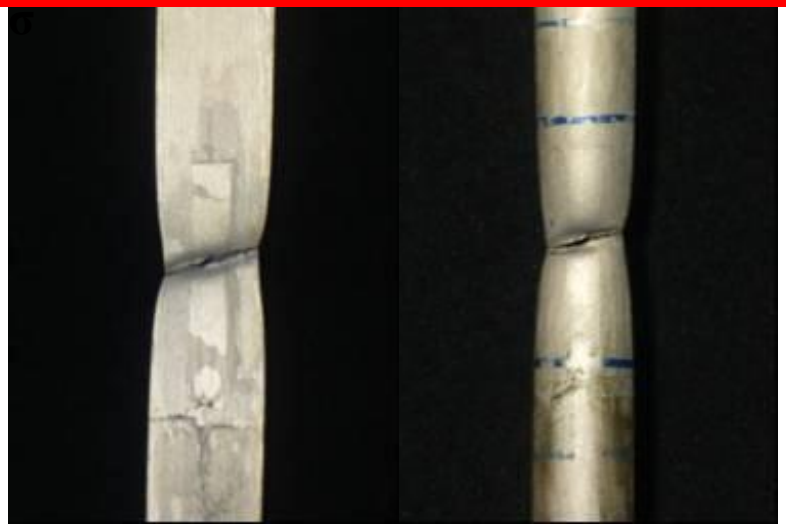
# Necking of Thin-Walled Materials under Uniaxial Tension




**Approximation:**

**Fracture strain ≈ strain at Point L**

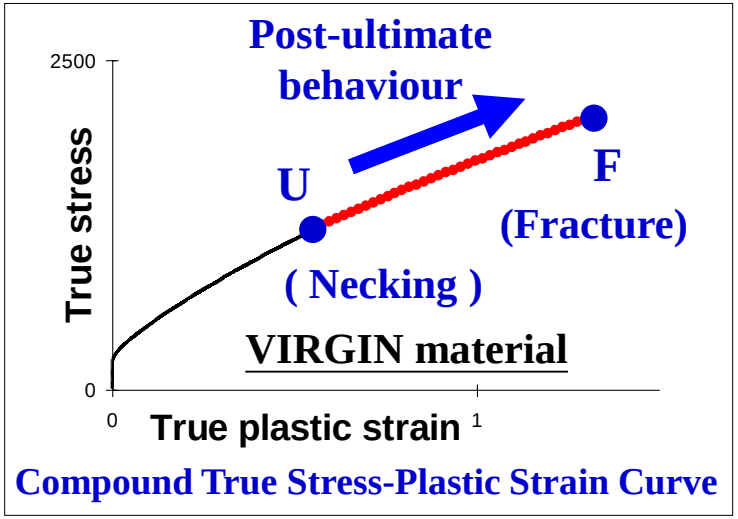
Flat coupon



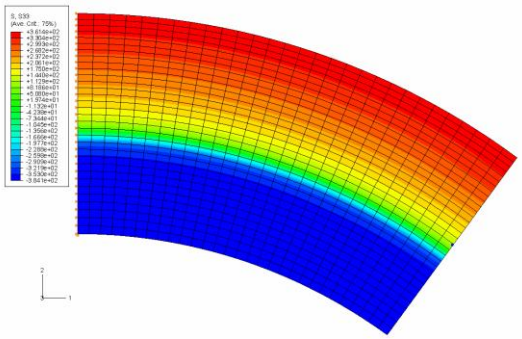
Corner coupon

# Advanced Numerical Approach – *Corner Mechanical Behaviour*

**Modified Weighted-Average Method (MWA)**



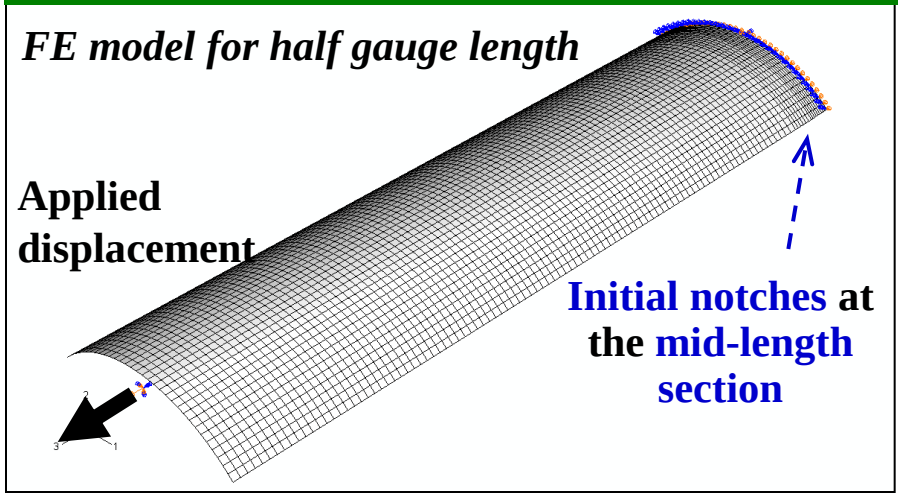

Compound True Stress-Plastic Strain Curve

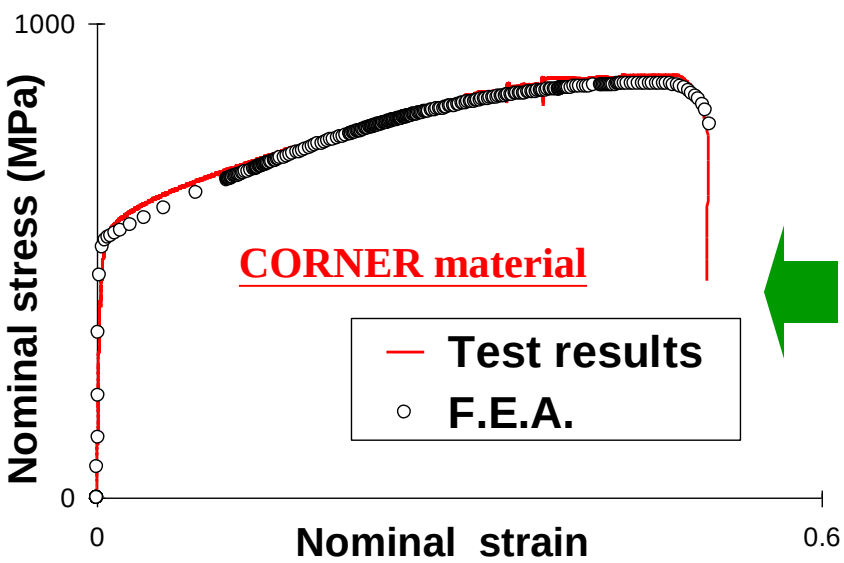


FE prediction of Residual Stresses & Equivalent Plastic Strains in Corners

## Numerical Corner Coupon Test

*FE model for half gauge length*



# Verification of Proposed Approach – *Experimental Study*

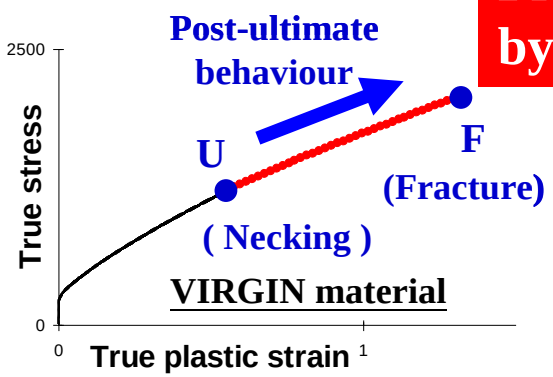
- **Two testing methods [ Single Corner (SC) test, Twin Corner (TC) test ]**
- **Totally 16 SC tests + 8 TC tests of press-braked corners**
- **Two batches of tests.**
- **Two grades (304, 316L) for each batch.**
- **Two inner corner radii (*ri* = 4 mm, 6 mm); thickness *t* = 2 mm.**
- **Flat coupon 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):**




**Fracture pt. by lab tests**

**True stress-plastic strain at Ultimate**

$$\sigma_t = \sigma_{t,u}\left[\underbrace{w(1+\varepsilon_{tp}-\varepsilon_{tp,u})}_{\text{Linear eq.}} + (1-w)\underbrace{\left(\frac{\varepsilon_{tp}}{\varepsilon_{tp,u}}\right)^{\varepsilon_{tp,u}}}_{\text{Power law}}\right]$$

**Weight constant**

- **Modified Weighted-Average Method (Present study):**

**True plastic strain at Fracture**

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

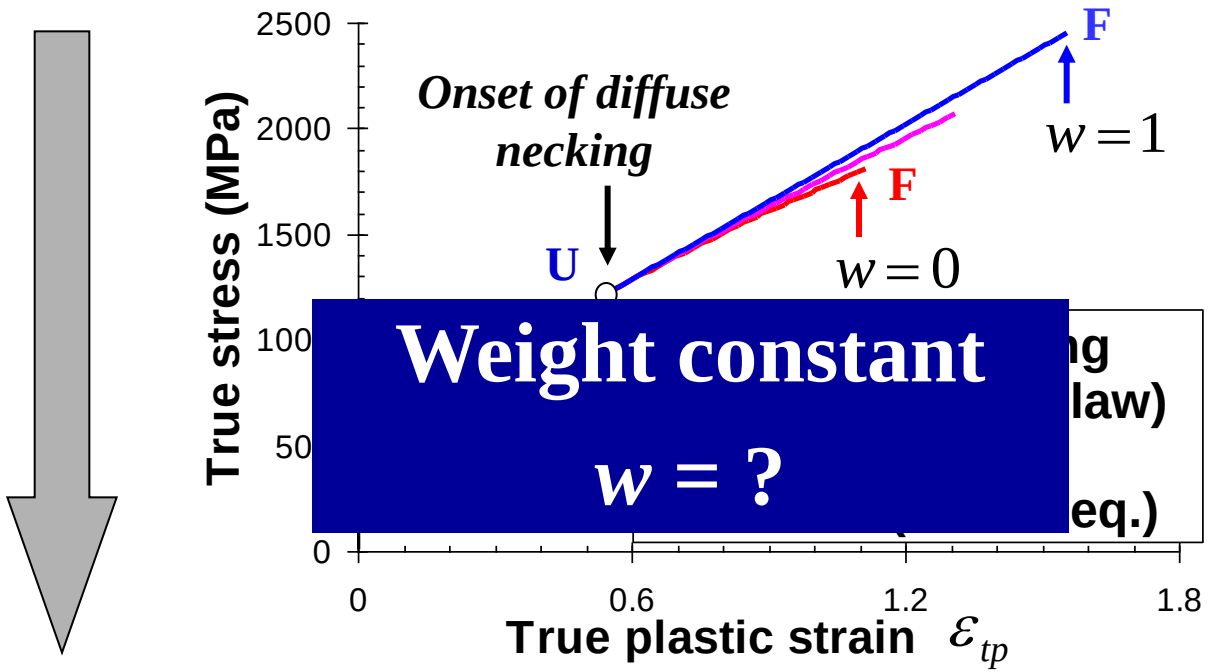
**Consider the effect of Material Anisotropy**

**Anisotropic metal:**

$$\bar{\sigma}=\sqrt{\frac{3}{2}\left(\frac{F+G}{F+G+H}\right)}\sigma_t \quad , \quad \bar{\varepsilon}_p=\sqrt{\frac{2}{3}\left(\frac{F+G+H}{F+G}\right)}\varepsilon_{tp}$$

# Modified Weighted-Average Method

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




**True plastic strain at fracture**

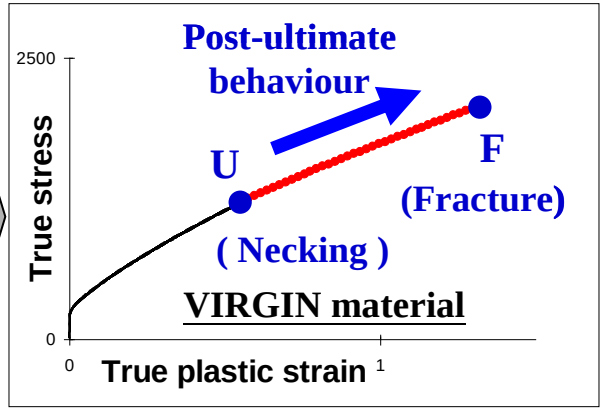
**Lower bound:** $\varepsilon_{tp,f}=(1+G/F)\varepsilon_{tp,u}$ **at** $w=0$

**Upper bound:** $\varepsilon_{tp,f}=\varepsilon_{tp,u}+G/F$ **at** $w=1$

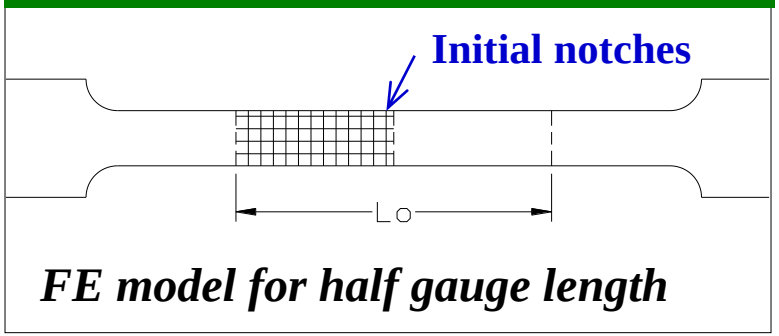
# Modified Weighted-Average Method – *Determination of Weight Constant & $\varepsilon_{tp,f}$*

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

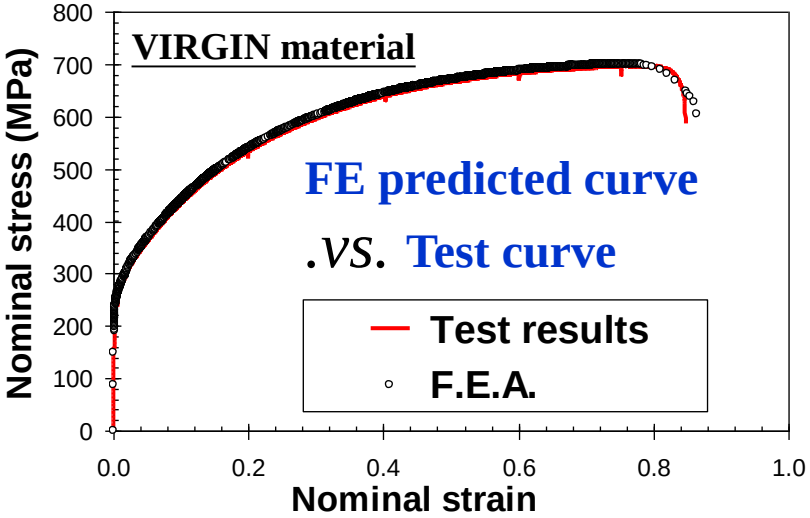
Trial weight constant $w$




**FE simulation of Flat Coupon Test**




( Inverse technique )



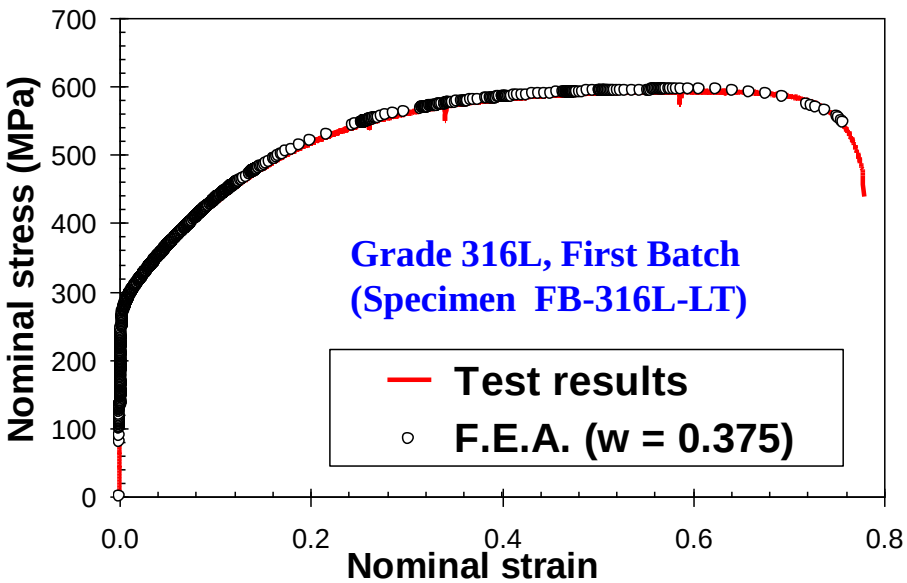

**FE prediction ≈ Test result**

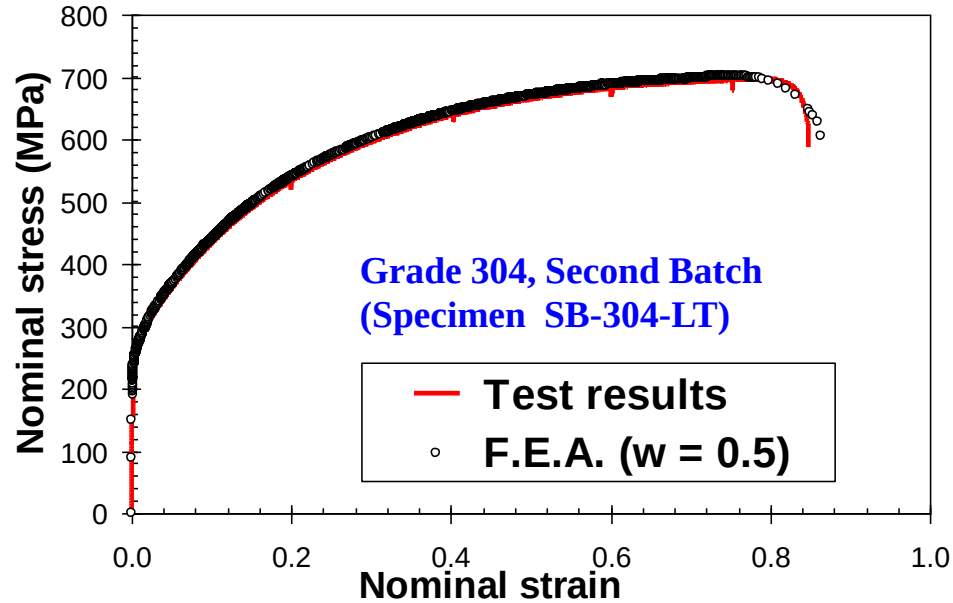
No

Yes

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

# Weight Constants for Virgin (Flat) materials




| Specimen | Weight constant, $w$ | True plastic strain $\varepsilon_{tp,f}$ at fracture | Percentage elongation after fracture | | |
|---|---|---|---|---|---|
| | | | Test result (1) | FEA (2) | (2)/(1) |
| FB-304-LT | 0.0 | 0.98 | 0.728 | 0.768 | 1.05 |
| FB-316L-LT | 0.375 | 0.95 | 0.793 | 0.757 | 1.05 |
| SB-304-LT | 0.5 | 1.31 | 0.848 | 0.865 | 0.98 |
| SB-316L-LT | 1.0 | 1.31 | 0.691 | 0.683 | 0.99 |

FB = First batch, SB = Second batch, LT = Longitudinal flat tension specimen.

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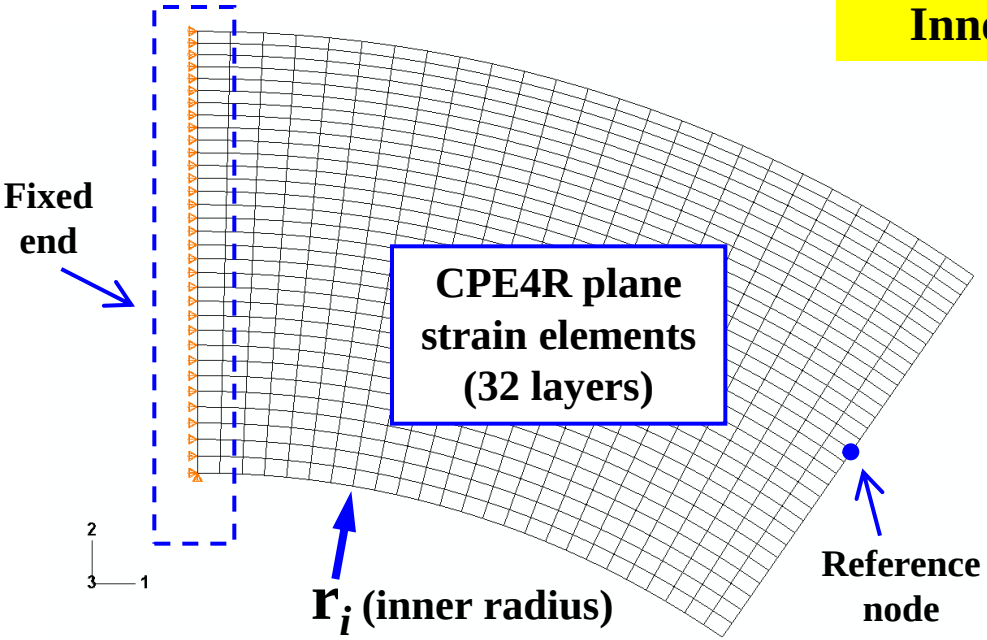
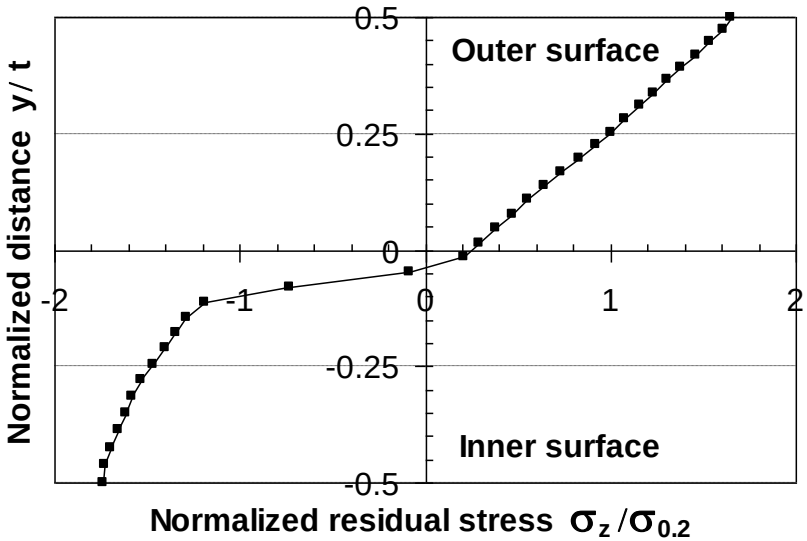
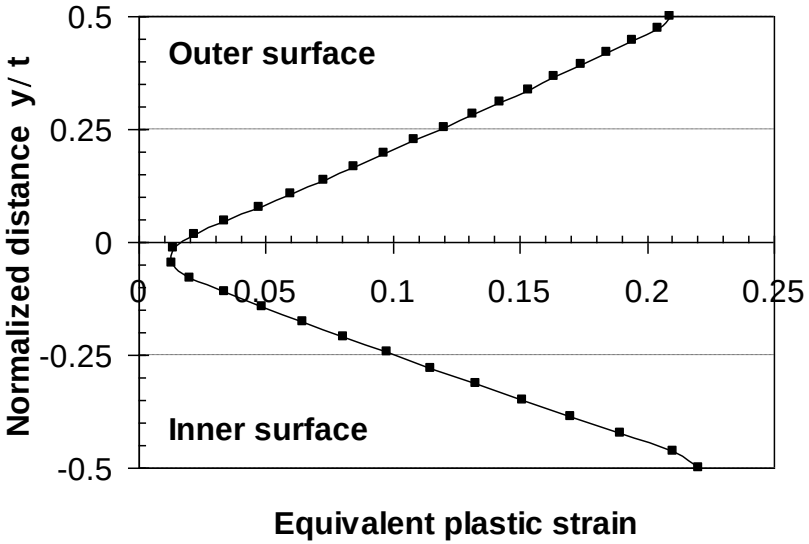
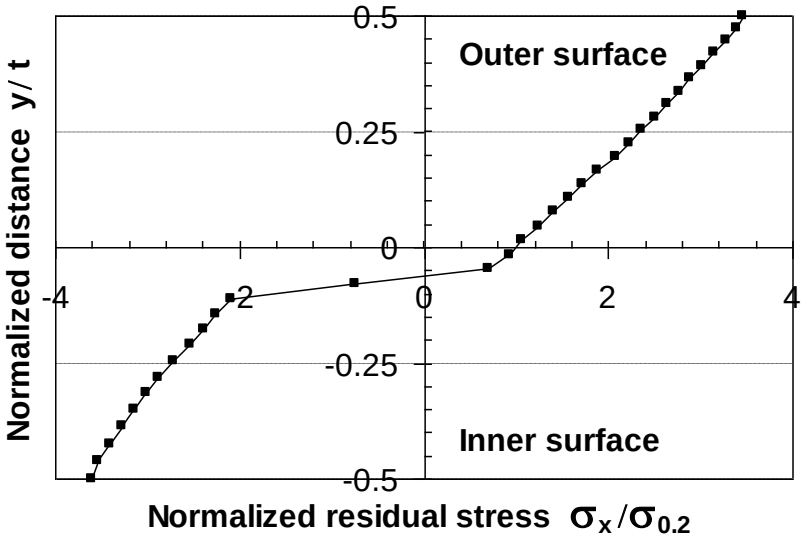
# FE Predictions of Residual Stresses in Corners

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



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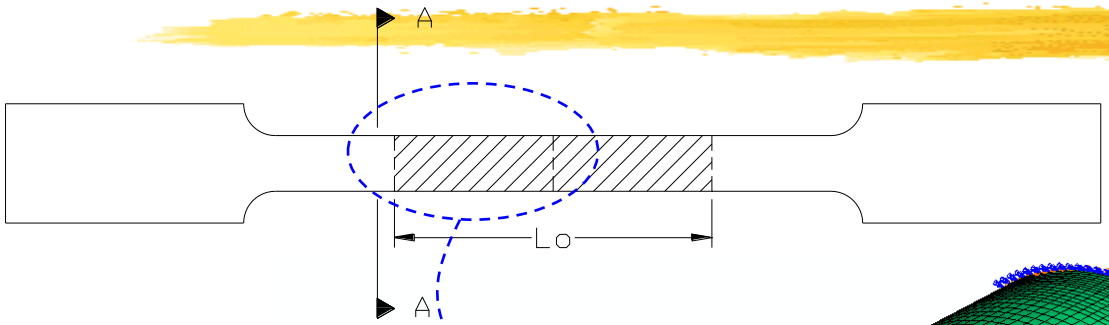
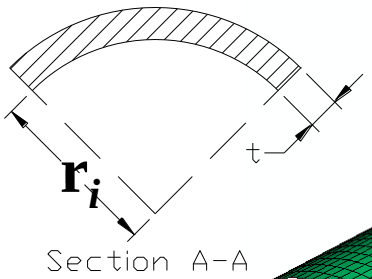
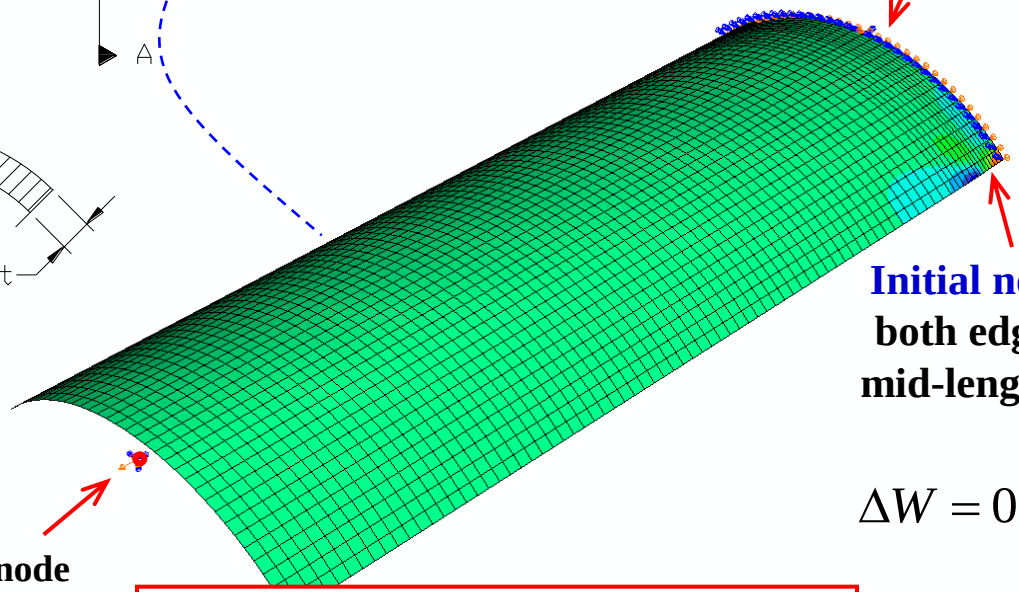
# FE Model for Corner Coupons



**Symmetrical boundary conditions at the mid-length section**

**Consider:**
- **Geometrical and material nonlinear**
- **Material anisotropy**

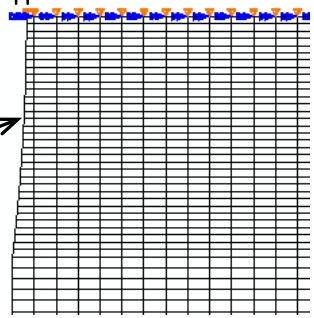
**Initial notches on both edges at the mid-length section**

**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

| Specimen | FEA/Test result | | |
|---|---|---|---|
| | $\sigma_{0.2,c}$ | $\sigma_{u,c}$ | $\varepsilon_{50,c}$ |
| FB-304-SCr4t2 | 1.15 | 1.02 | N.A. |
| FB-304-TCr4t2 | 1.11 | 0.98 | 1.01 |
| FB-304-SCr6t2 | 1.26 | 1.04 | 1.02 |
| FB-304-TCr6t2 | 1.27 | 1.01 | 1.01 |
| SB-304-SCr4t2* | 1.13 | 0.95 | 0.99 |
| SB-304-SCr6t2* | 1.07 | 0.93 | 1.09 |
| SB-304-TCr6t2* | 1.11 | 0.96 | 1.11 |
| FB-316L-SCr4t2 | 1.22 | 1.07 | N.A. |
| FB-316L-TCr4t2 | 1.15 | 0.98 | 0.91 |
| FB-316L-SCr6t2 | 1.04 | 1.00 | N.A. |
| FB-316L-TCr6t2 | 1.10 | 0.97 | 0.94 |
| SB-316L-SCr4t2* | 1.10 | 0.96 | 1.09 |
| SB-316L-SCr6t2* | 1.03 | 0.94 | 1.13 |
| SB-316L-TCr6t2* | 1.08 | 0.94 | 1.04 |
| **Mean** | **1.11** | **0.97** | **1.05** |
| **Std. dev.** | **0.07** | **0.04** | **0.07** |

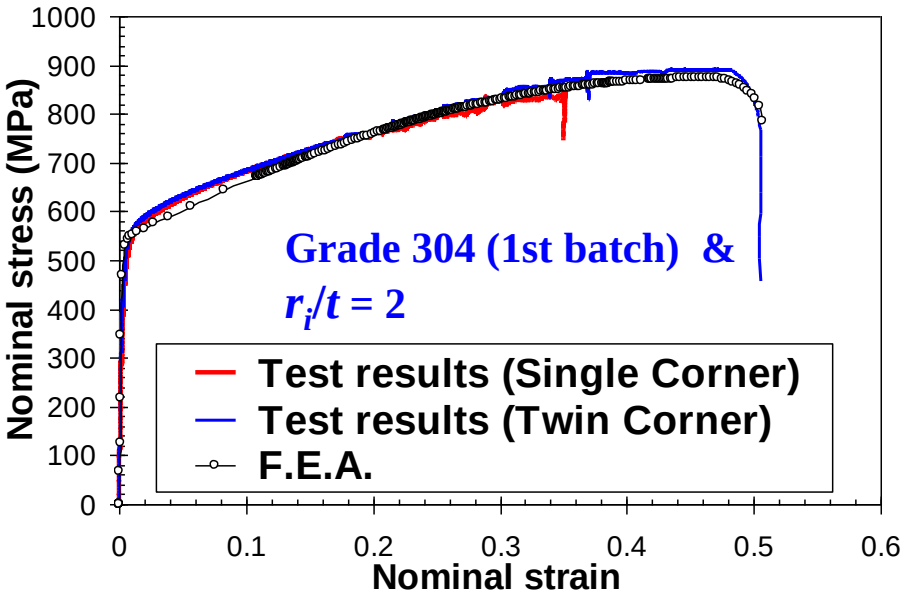
$\sigma_{0.2,c}$ = Corner 0.2% proof stress

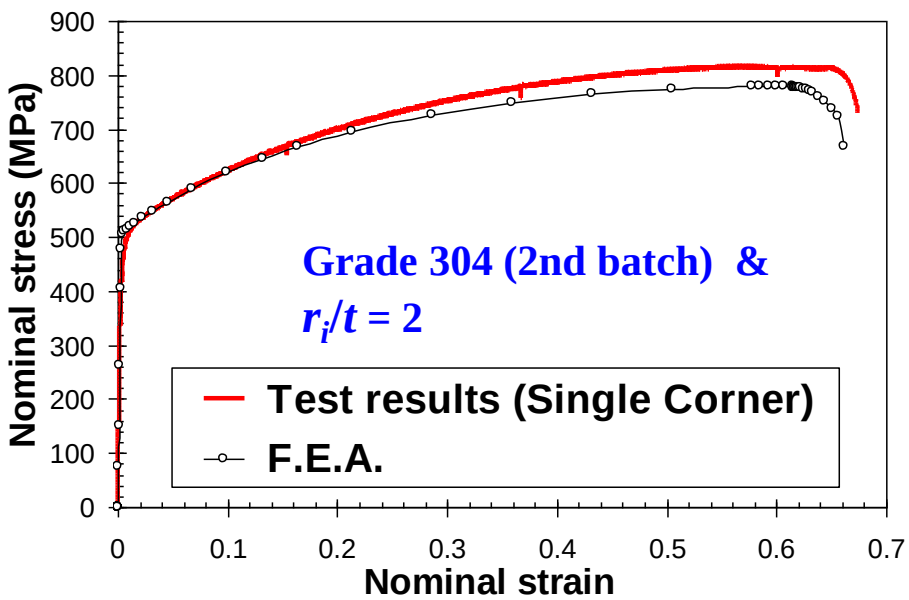
$\sigma_{u,c}$ = Corner ultimate strength

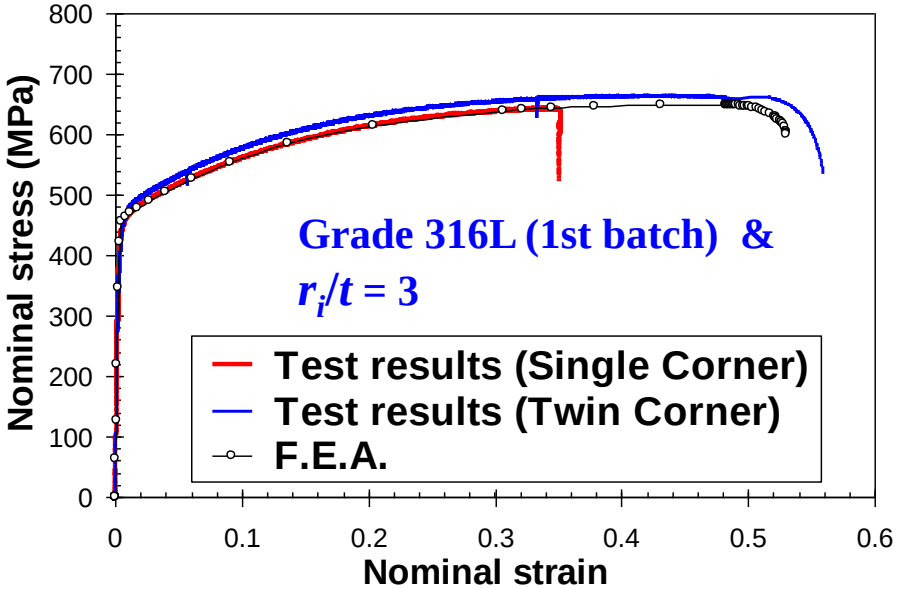
$\varepsilon_{50,c}$ = Percentage elongation after fracture over a 50-mm gauge length of a corner

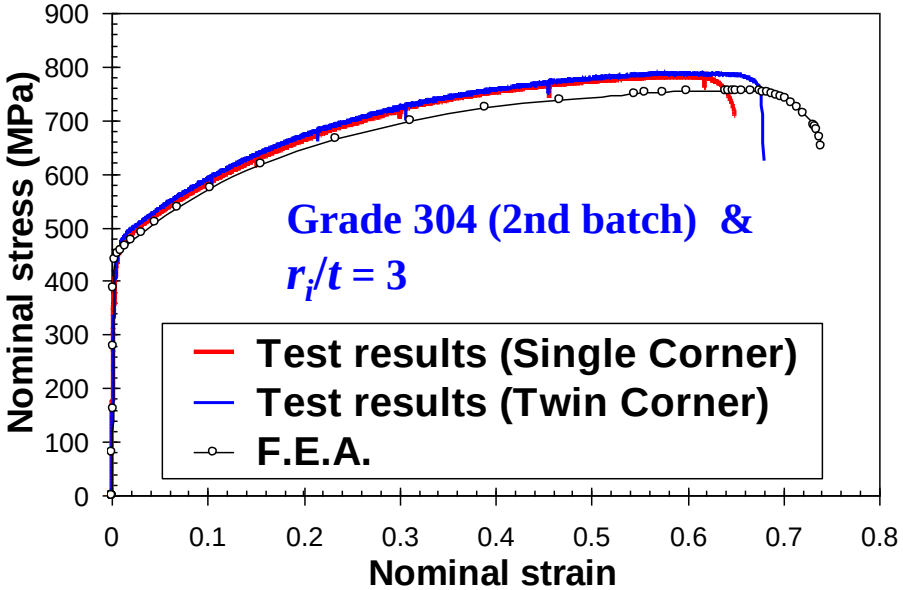
**** Average value of repeated tests***

# Comparisons with Test Results



# Comparisons with Existing Empirical Models: Corner 0.2% Proof Stress $\sigma_{0.2,c}$

| Specimen | Prediction/Test result | | | |
|---|---|---|---|---|
| | Van den Berg & Van der Merwe (1992) | *Simple model* (Ashraf et al. 2005) | *Power model* (Ashraf et al. 2005) | Proposed F.E.A. |
| FB-304-SCr4t2 | 0.56 | 0.98 | 0.84 | 1.15 |
| FB-304-TCr4t2 | 0.53 | 0.94 | 0.80 | 1.11 |
| FB-304-SCr6t2 | 0.64 | 1.12 | 0.90 | 1.26 |
| FB-304-TCr6t2 | 0.64 | 1.13 | 0.90 | 1.27 |
| SB-304-SCr4t2* | 0.43 | 0.88 | 0.73 | 1.13 |
| SB-304-SCr6t2* | 0.43 | 0.88 | 0.68 | 1.07 |
| SB-304-TCr6t2* | 0.45 | 0.92 | 0.70 | 1.11 |
| FB-316L-SCr4t2 | 0.93 | 1.03 | 1.00 | 1.22 |
| FB-316L-TCr4t2 | 0.88 | 0.97 | 0.94 | 1.15 |
| FB-316L-SCr6t2 | 0.84 | 0.91 | 0.87 | 1.04 |
| FB-316L-TCr6t2 | 0.89 | 0.96 | 0.92 | 1.10 |
| SB-316L-SCr4t2* | 0.73 | 0.85 | 0.82 | 1.10 |
| SB-316L-SCr6t2* | 0.71 | 0.83 | 0.77 | 1.03 |
| SB-316L-TCr6t2* | 0.75 | 0.87 | 0.81 | 1.08 |
| **Mean** | **0.63** | **0.91** | **0.80** | **1.11** |
| **Std. dev.** | **0.17** | **0.08** | **0.09** | **0.07** |

# Existing Empirical Models for Stainless Steel Corner Strength

**From Ashraf *et al*. (2005):**

**Simple model**

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

**Yield strength and ultimate strength of VIRGIN sheets**

**Power model**

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

**Functions of VIRGIN material properties**

***Linear Eq.***

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

# Comparisons with Existing Empirical Models: Corner Ultimate Strength $\sigma_{u,c}$

| Specimen | Prediction/Test result | | |
|---|---|---|---|
| | *Simple model* (Ashraf et al. 2005) | *Power model* (Ashraf et al. 2005) | Proposed F.E.A. |
| FB-304-SCr4t2 | 1.13 | 0.96 | 1.02 |
| FB-304-TCr4t2 | 1.08 | 0.92 | 0.98 |
| FB-304-SCr6t2 | 1.10 | 0.88 | 1.04 |
| FB-304-TCr6t2 | 1.06 | 0.85 | 1.01 |
| SB-304-SCr4t2* | 1.05 | 0.87 | 0.95 |
| SB-304-SCr6t2* | 0.98 | 0.76 | 0.93 |
| SB-304-TCr6t2* | 1.02 | 0.78 | 0.96 |
| FB-316L-SCr4t2 | 1.17 | 1.14 | 1.07 |
| FB-316L-TCr4t2 | 1.06 | 1.04 | 0.98 |
| FB-316L-SCr6t2 | 1.05 | 1.00 | 1.00 |
| FB-316L-TCr6t2 | 1.02 | 0.97 | 0.97 |
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| **Mean** | **1.03** | **0.90** | **0.97** |
| **Std. dev.** | **0.05** | **0.10** | **0.04** |

# 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