GREAT DESIGNS IN STEEL™

## GDIS Technical Webinar Series:

# A novel approach for precise calibration of force-based RSW failure criteria implemented in LS-DYNA

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# Presentation outline

## Introduction

- 3G-AHSS
- RSW Process
- RSW Failure Prediction
- RSW Component Tests
- Research Motivation

## Task 1

- Process Optimization
- Weldability Lobes
- Failure Surfaces

## Task 2

- Shear-tensile Loading via KS-II Tests
- Failure Loci Assessment in Shear-tensile Mode

## Task 3

- Tensile-bending Loading via Coach Peel Tests
- Failure Loci Assessment in Tensile-bending Mode

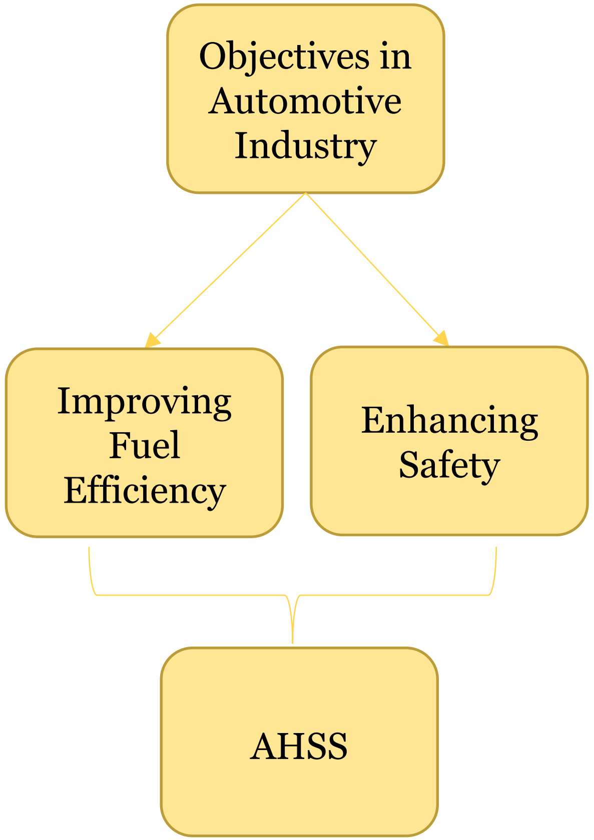
## Task 4

- Tensile-bending Loading of Weld-groups (Component Tests)
- Mechanical Properties
- Failure Behavior
- LS-DYNA Simulations

## Conclusions

- Main Conclusions

# Third Generation Advanced High Strength Steels (3G-AHSS)

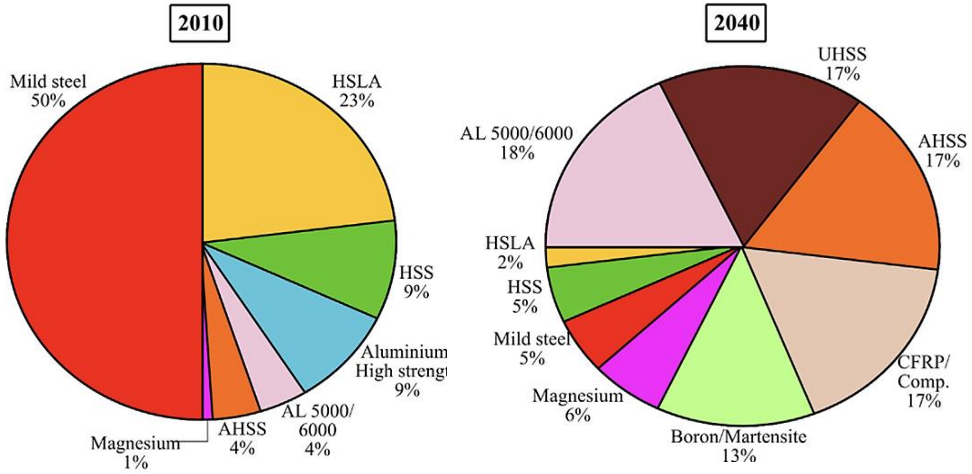


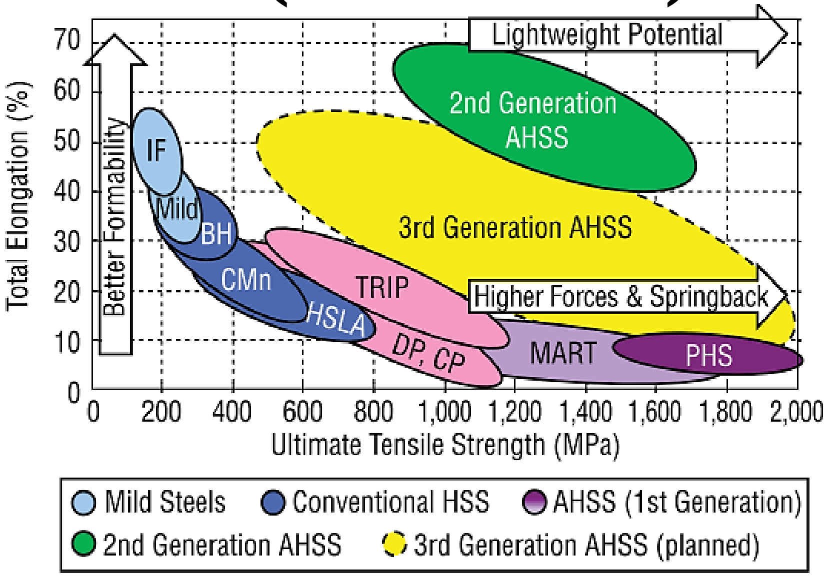
Objectives in Automotive Industry

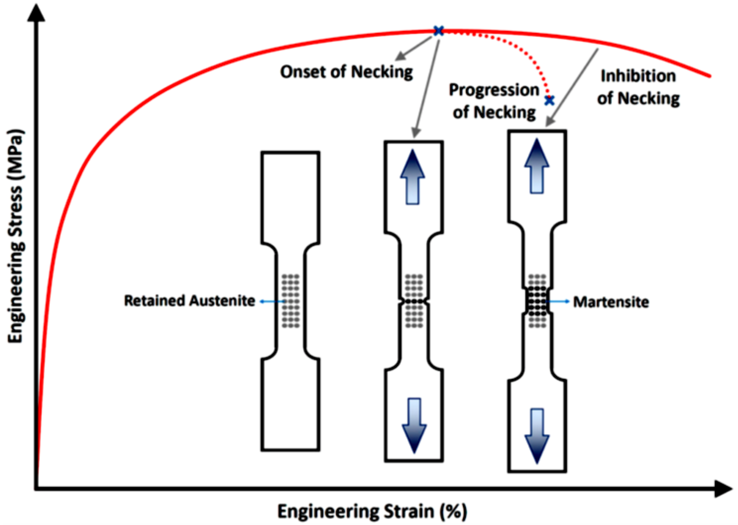
Improving Fuel Efficiency

Enhancing Safety

AHSS





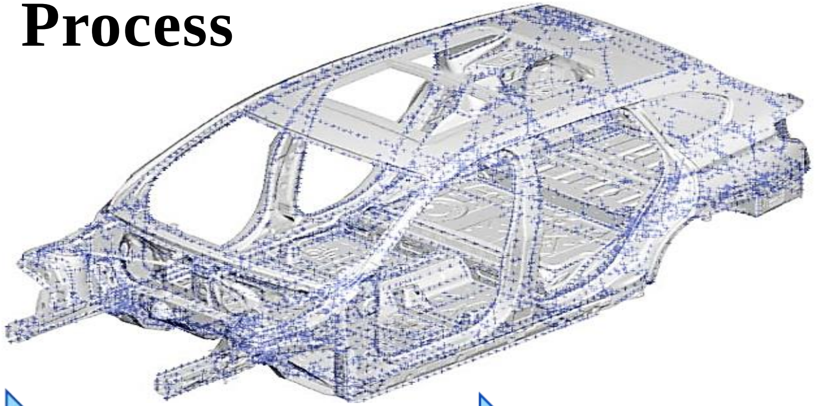


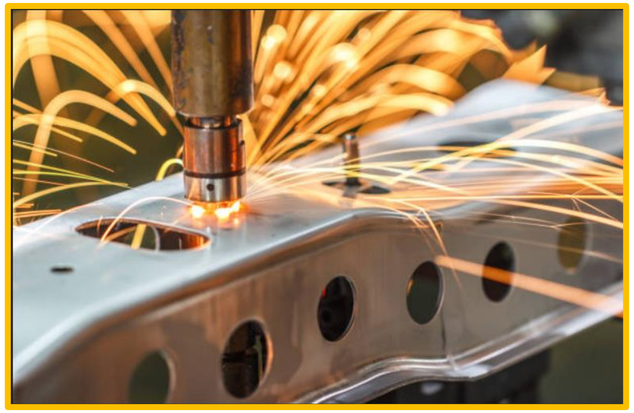
[1] Giampieri et al, *Applied Energy* (2020)
[2] Zhao et al, *Progress in Materials Science* (2018)
[3] Soleimani et al, *Materials Science and Engineering* (2020)

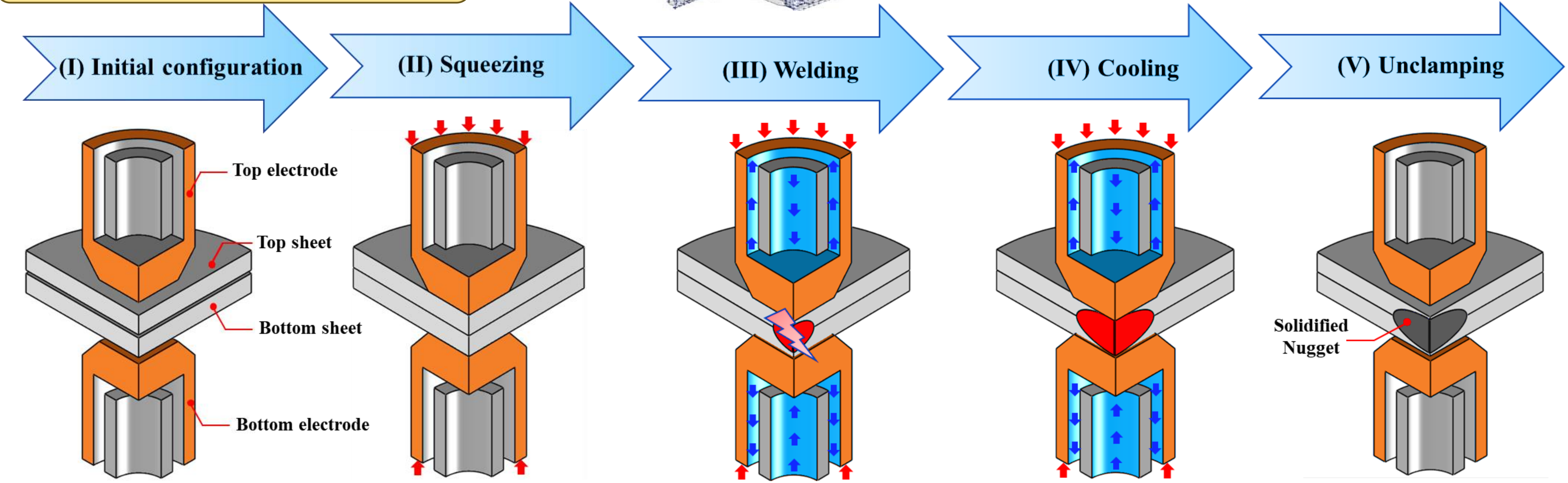
# Resistance Spot Welding (RSW) Process

RSW is the most common joining technique in the automotive industry

5000 Spot Welds in a typical body-in-white on average







**(I) Initial configuration**

**(II) Squeezing**

**(III) Welding**

**(IV) Cooling**

**(V) Unclamping**

**Predicting failure of spot welds is a priority for the automotive industry**

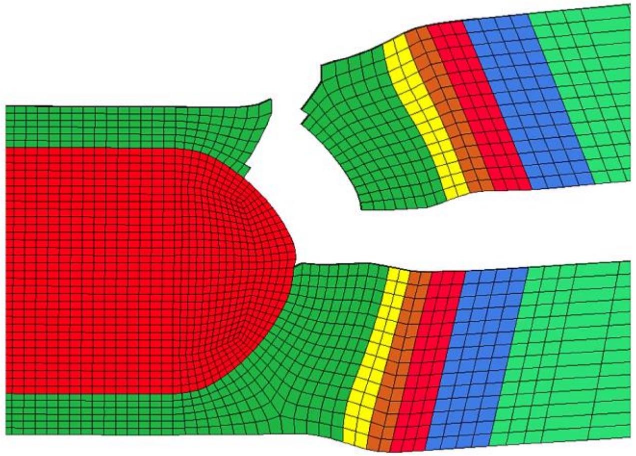
[4] *Zerohourparts.com* (2024)

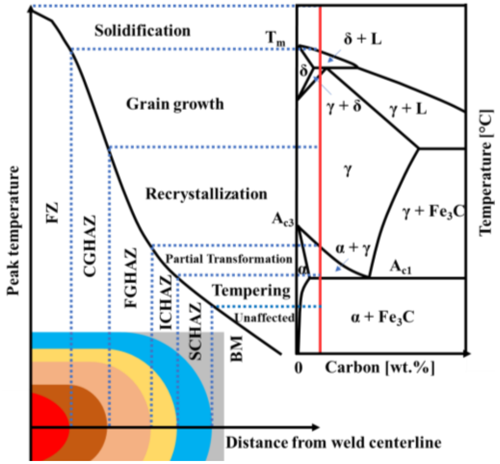
# RSW Failure Prediction:

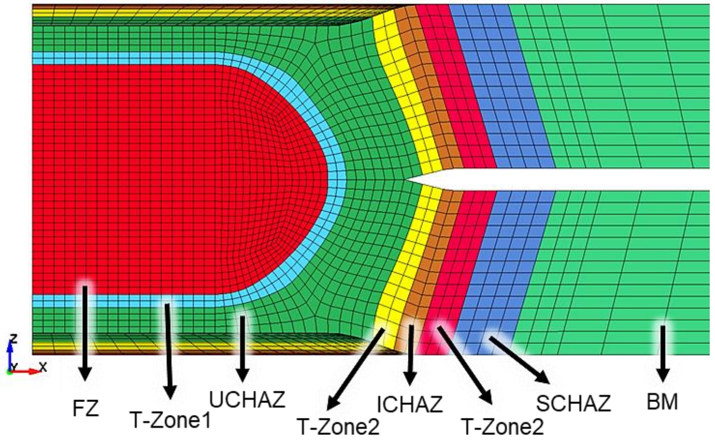
## 1. Mesoscale models (fine mesh + constitutive properties of sub-zones)

⬆ Informative regarding mechanics of fracture

⬇ Computationally demanding,
Requires fracture characterization of sub-zones



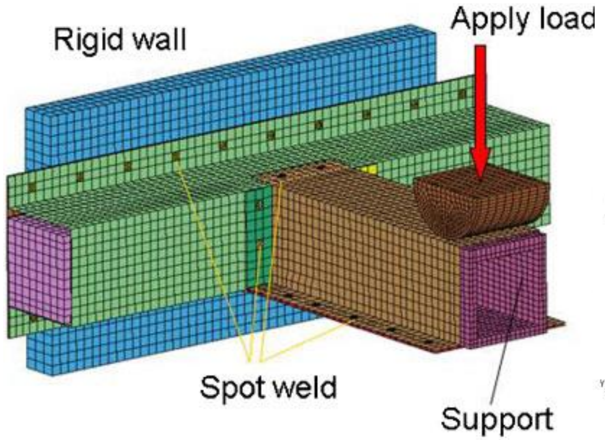


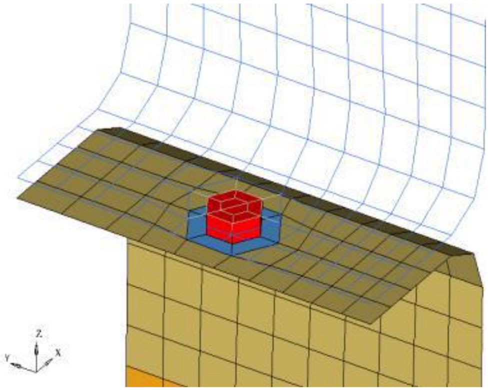


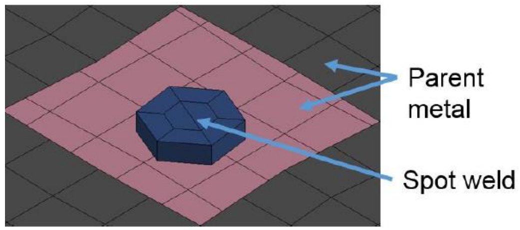
## 2. Force-based models (coarse mesh + interpolated failure loci from mechanical tests)

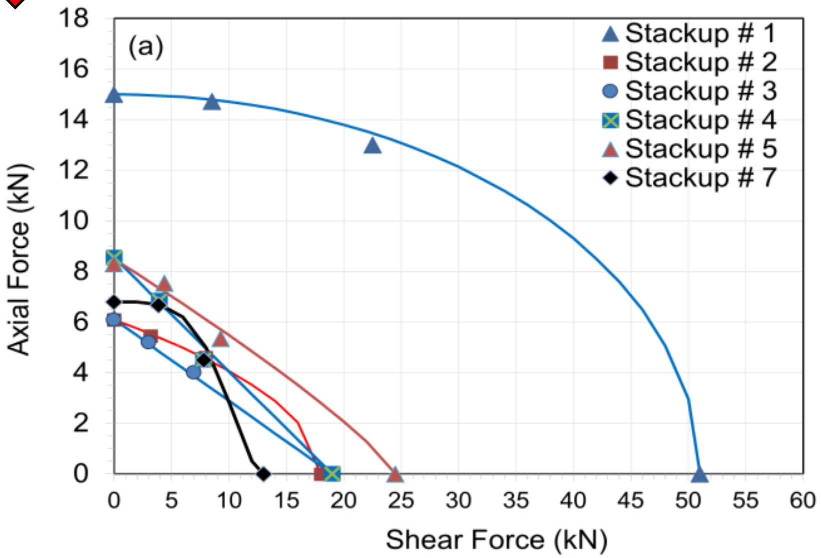
⬆ Well-suited for industrial applications

⬇ Limited insight into mechanics of failure









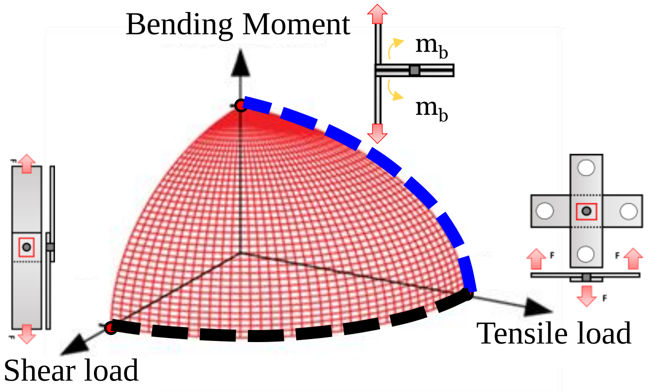
[5] Mohamadizadeh Ph.D. *Thesis* (2020)
[6] Ghassemi-Armaki et al. *Int J Mech Sci* (2011)
[7] Midawi et al. *Forces in Mech* (2022)

# Load-based RSW Failure Criteria:

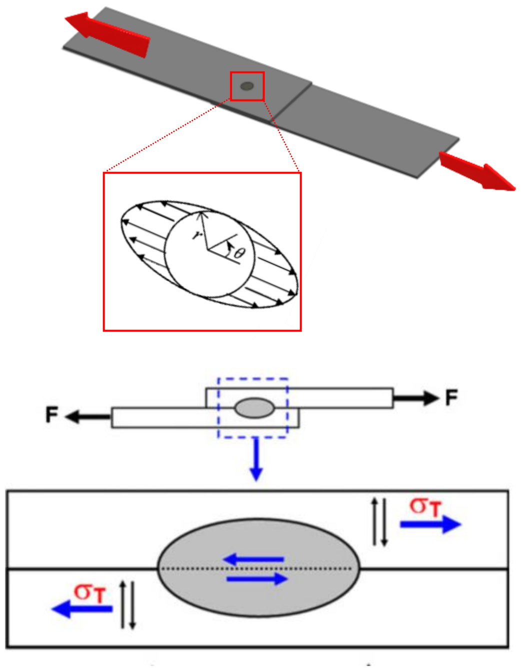
Failure equation in
LS-DYNA *MAT_100_DA
material model:

$$f^{Seeger} = \left[\frac{f_s}{S_S(\dot{\varepsilon}_{eff})}\right]^a + \left[\frac{f_n}{S_N(\dot{\varepsilon}_{eff})}\right]^b + \left[\frac{m_b}{S_B(\dot{\varepsilon}_{eff})}\right]^c \geq 1$$

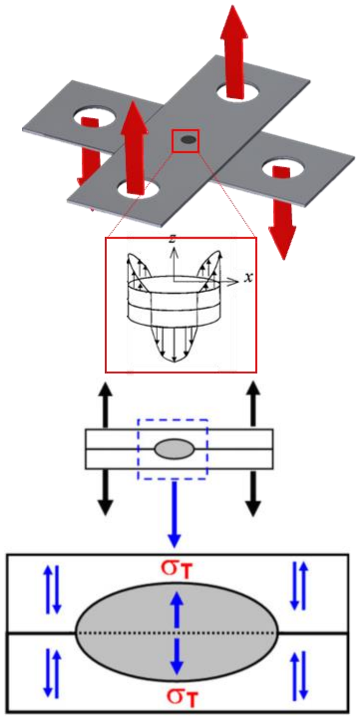
Shear strength | Tensile strength | Bending strength



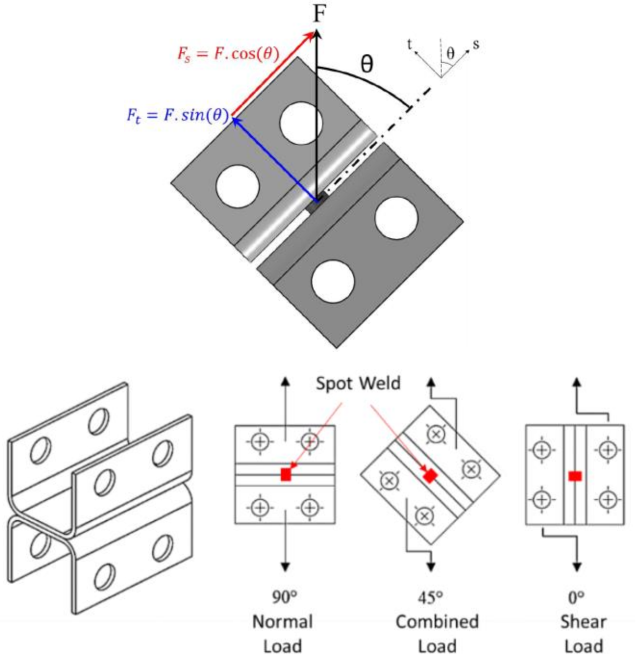
## Lap Shear Test



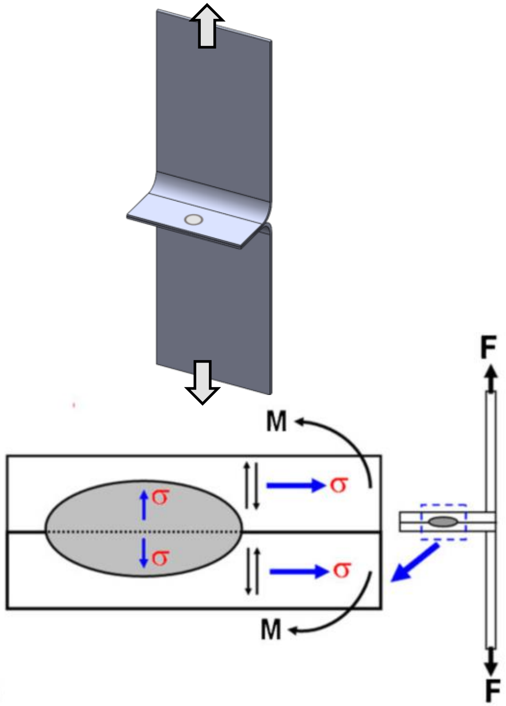
## Cross-tension Test



## KS-II Test

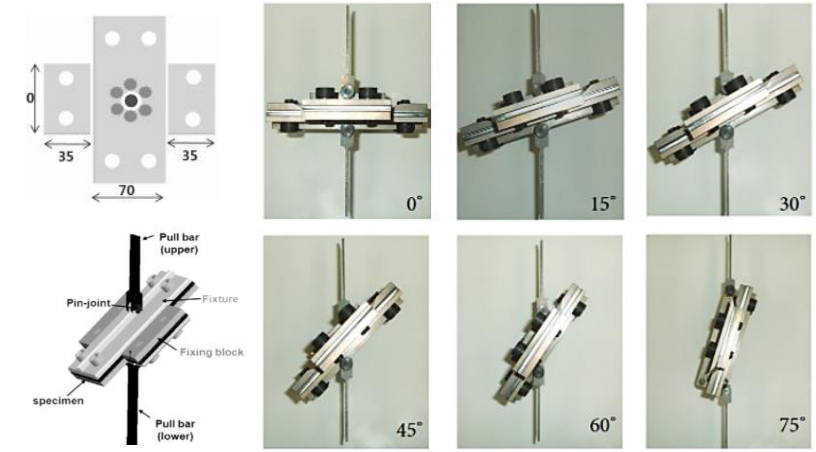


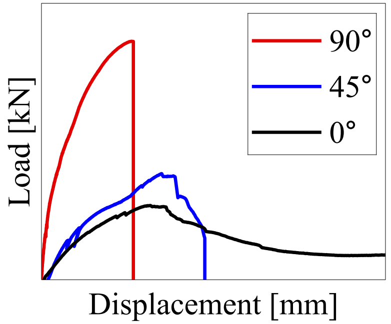
## Coach Peel Test



[8] Song JH, Huh H. *Int J Mech Sci* (2011)
[9] Pouranvari et al, *J Mater Eng Perform* (2012)
[10] Seeger, F., et al. *4th LS-DYNA User Forum*, (2008)

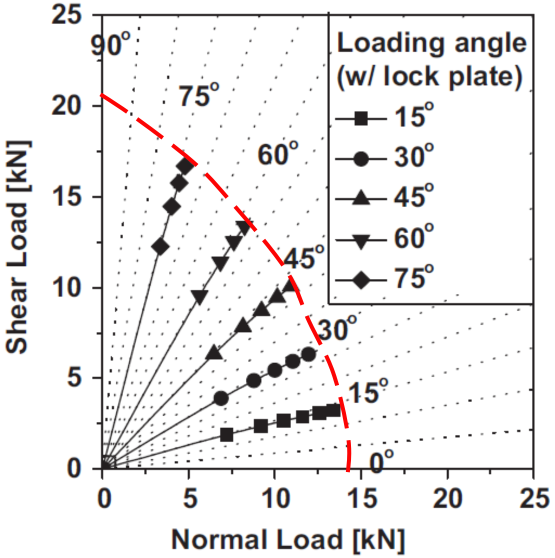
# Combined Shear-tensile Loading of Spot Welds

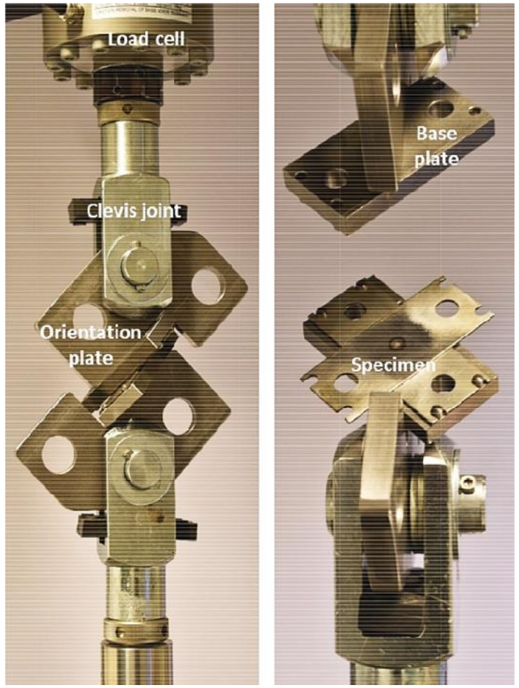


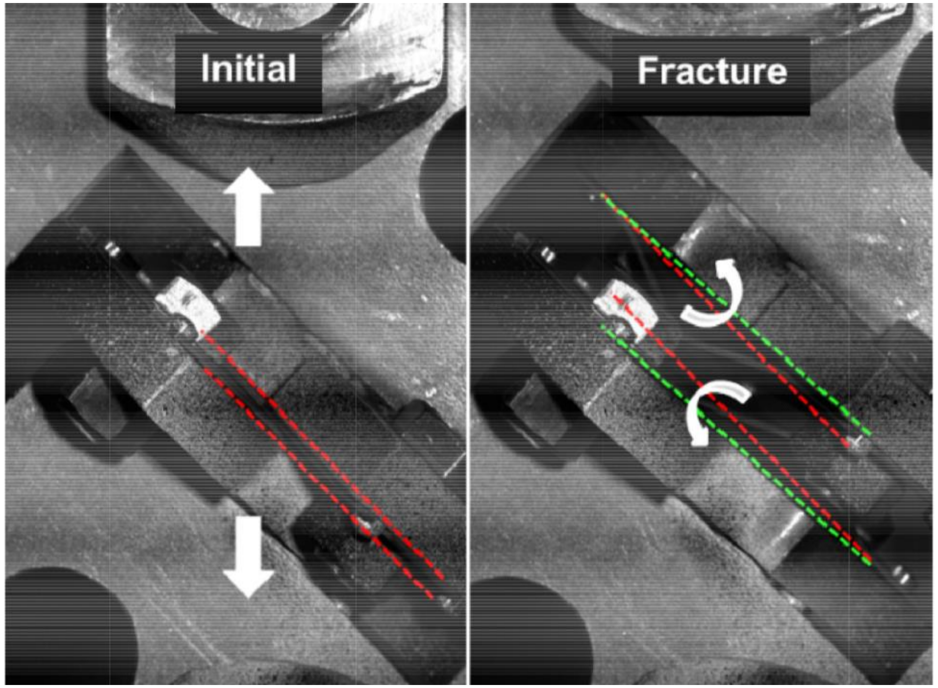


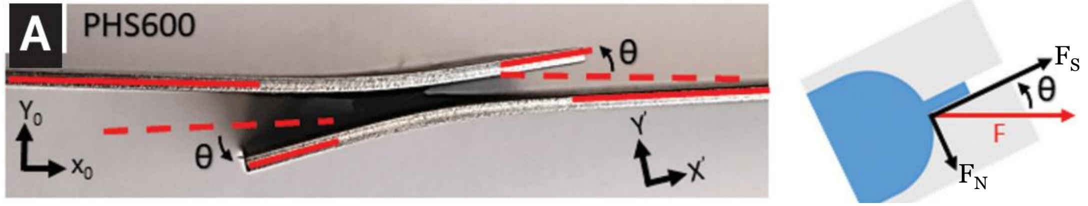
$$F_{Shear} = F.\cos(\theta)$$

$$F_{Tensile} = F.\sin(\theta)$$









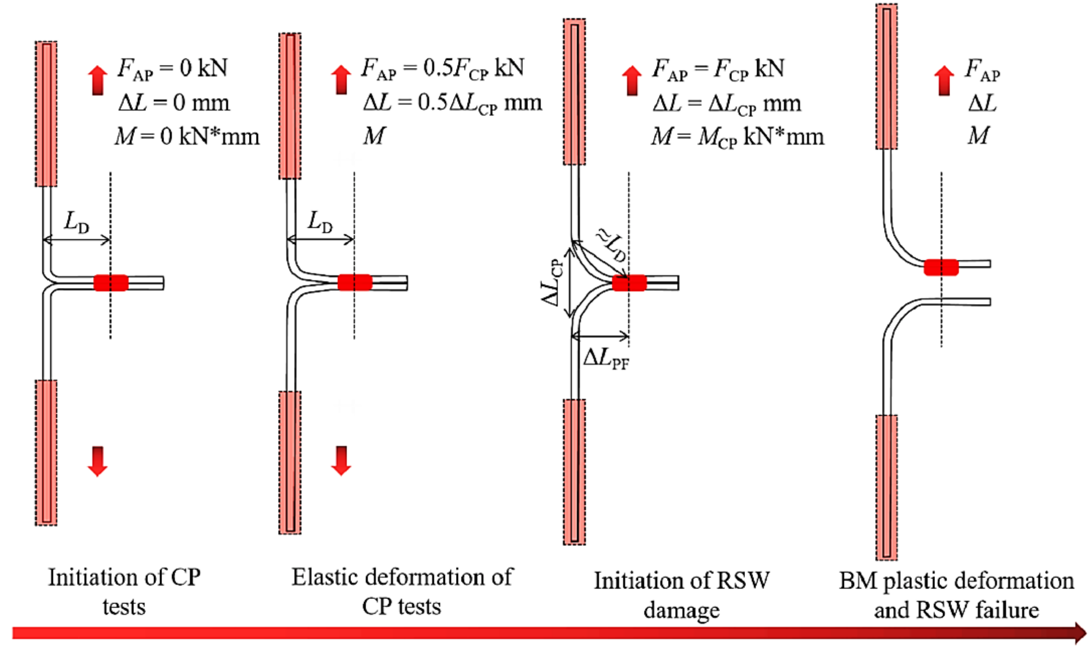
**Deficiencies in shear/tensile loading of spot welds:**

- Quantification of coupon slippage and rotation
- Inaccurate critical shear and tensile load components

[11] Pandya et al. *Int J Mech Sci* (2020)
[12] Lin et al. *Int J Solids Struct* (2022)
[13] Ha et al. *Int J Mech Sci* (2013)
[14] Mohamadizadeh et al. *Weld Res* (2019)

# Combined Tensile-bending Loading of Spot Welds

$$f^{Seeger} = \left[\frac{f_n}{S_N(\dot{\varepsilon}_{eff})}\right]^a + \left[\frac{f_s}{S_S(\dot{\varepsilon}_{eff})}\right]^b + \boxed{\left[\frac{m_b}{S_B(\dot{\varepsilon}_{eff})}\right]^c} \geq 1$$



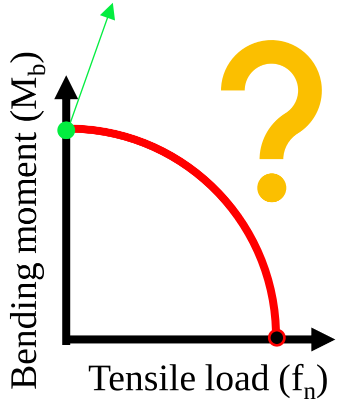
$$M_{CP} = F_{CP} \times \Delta L_{PF}$$

Bending moment

Load

Moment arm

$$S_B = \frac{F_{Max\ CP} \times d}{\sqrt{1 - \left(\frac{F_{Max\ CP}}{F_{Max\ KS-II\ 90°}}\right)}}$$



**Deficiencies in tensile/bending loading of spot welds:**

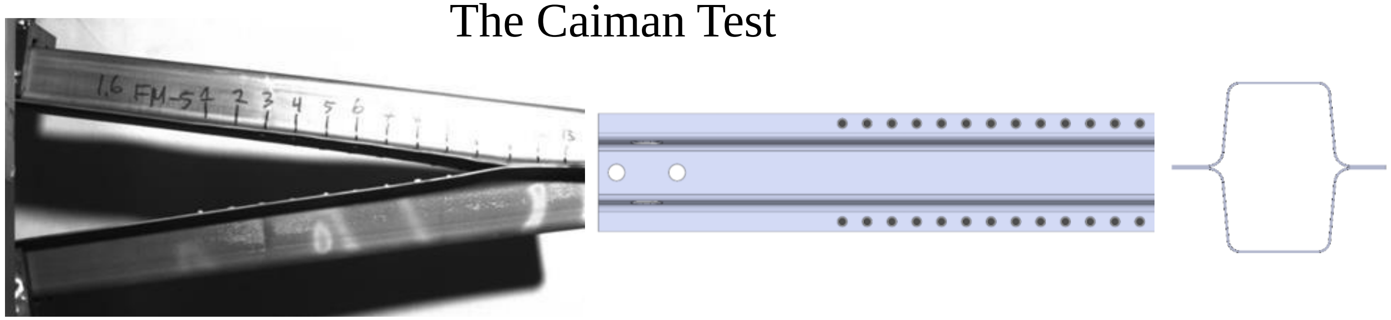
- No assessment of convex failure loci assumption
- Idealized deformation of the coach peel coupon
- Unknown evolution of bending moment and its value at the onset of failure

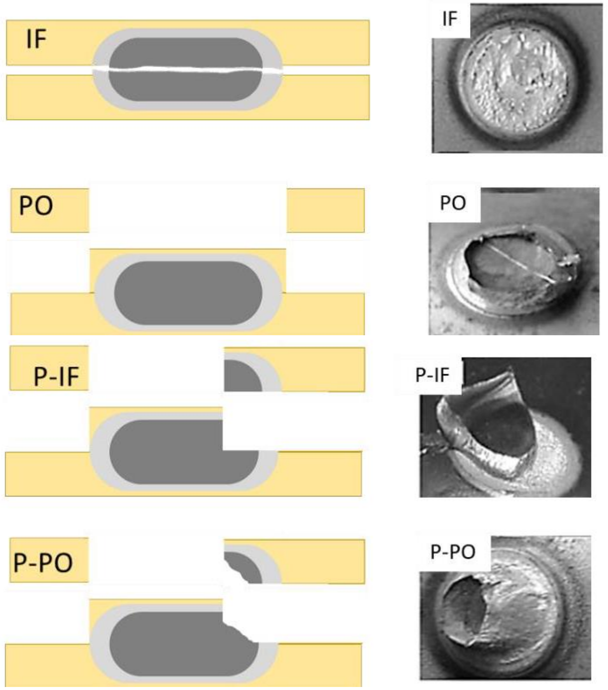
[15] Xu et al. *Eng Frac Mech* (2023)
[16] Pouranvari et al. *Iron Steel Proc* (2012)
[17] Arumugam et al. *J Mech Eng* (2022)
[18] Shashikumar et al. *Metals* (2023)
[19] Wang et al. *Int J Crash* (2018)

# Tensile-bending Loading of Groups of Spot Welds

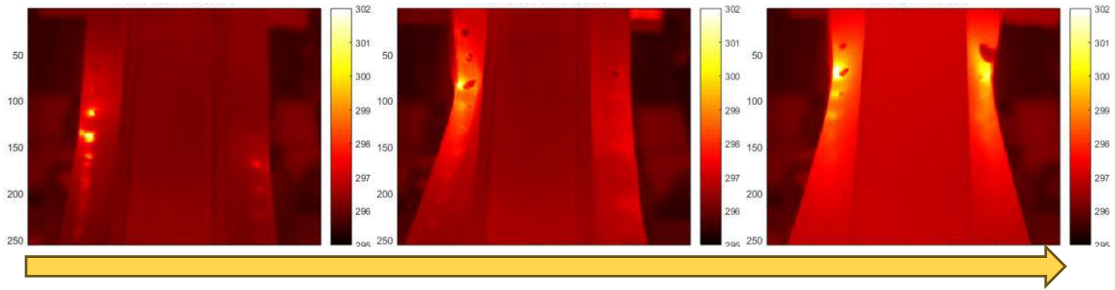
Purpose for Performing Weld-group Tests → Characterization of sequential failure between welds and validate models

The Caiman Test





**Fully Quenched Flange** | **400 °C Tailored Flange** | **700 °C Tailored Flange**



**Increase in flange ductility** | **Higher flange deformation**

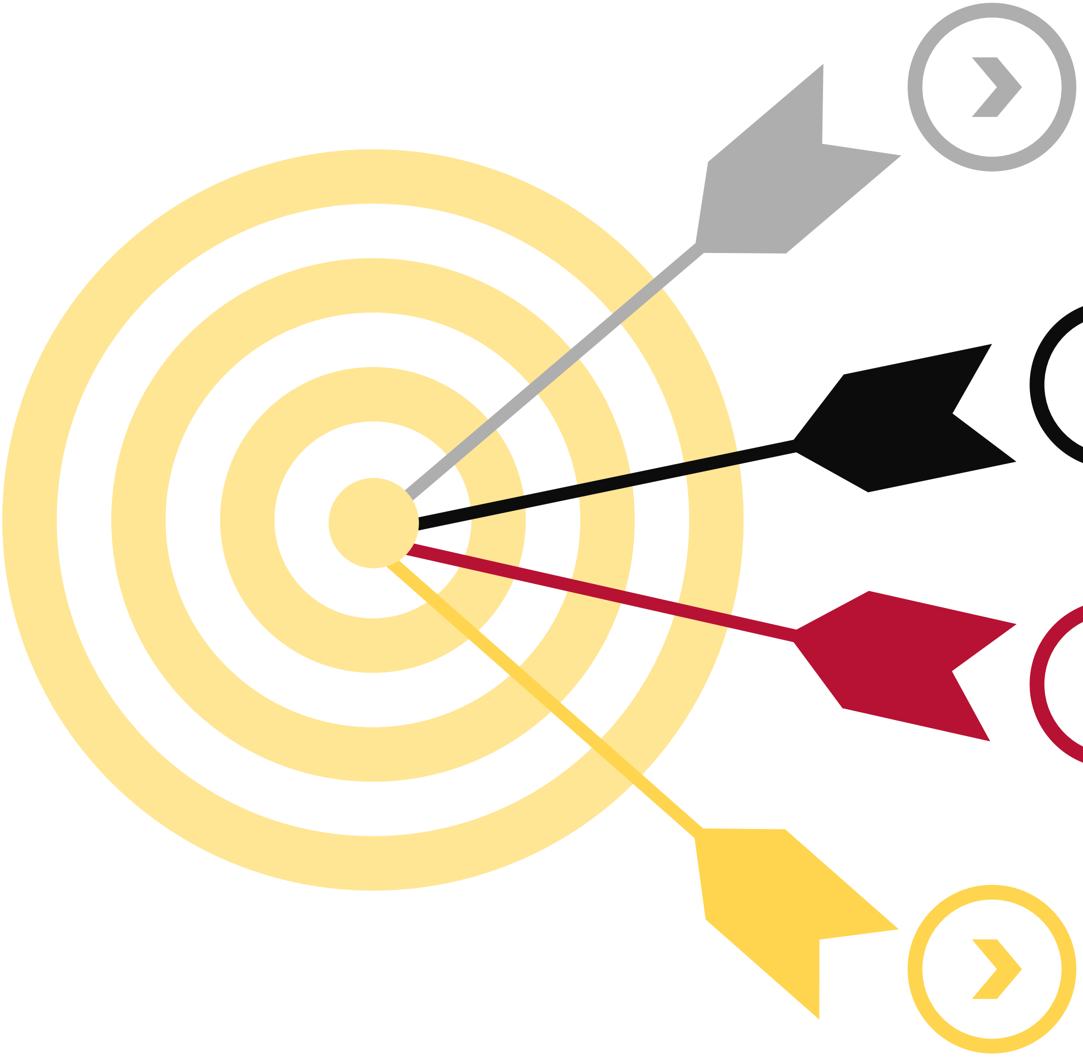
**Improved Energy Absorption**

**Deficiencies in tensile-bending loading of spot weld groups:**

- How does failure mode affect the mechanical performance of weld groups?
- What are the factors that dictate energy absorption capability?

[20] Tolton et al, *Master's Thesis* (2021)
[21] O'Keeffe et al, *Master's Thesis* (2018)
[22] Mohamadizadeh et al, *Exp Mech* (2022)

# Motivation Based on the Identified Gaps Within the Literature:



**Process Optimization**

Selecting a Suitable Welding Current That Produces Expulsion-free Joints with the Highest Load Bearing Capacity and Energy Absorption Capability

**Mechanical Properties of Joints Under Shear/Tensile Loading**

Assess the Validity of Seeger’s Proposed Failure Loci in Shear-tensile Loading Conditions via KS-II Tests

**Mechanical Properties of Joints Under Tensile/Bending Loading**

Assess the Validity of Seeger’s Proposed Failure Loci in Tensile-bending Loading Conditions via Coach Peel Tests

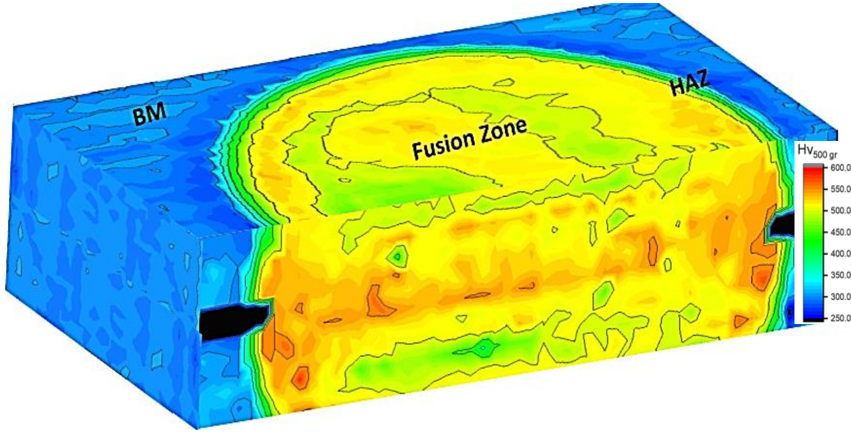
**Mechanical Properties of Groups of Joints Under Tensile/Bending Loading**

Critical Factors Influencing Mechanical Performance of The Caiman Mode I Components

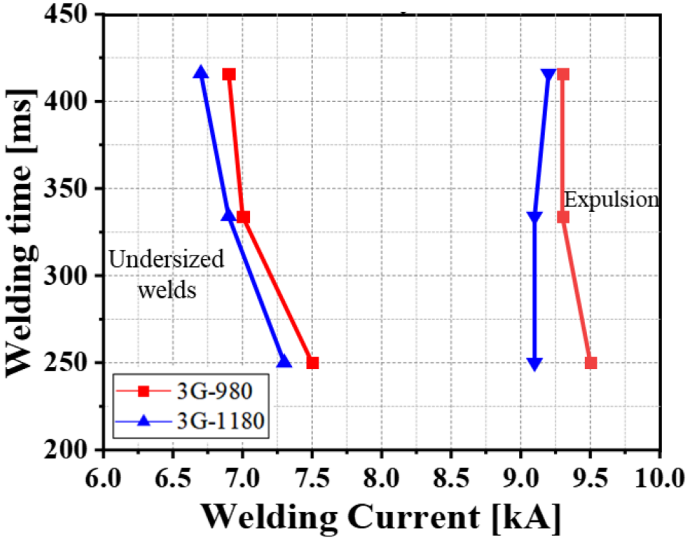
# Task 1

# RSW Process Optimization and Seeger's Nominal Failure Surfaces

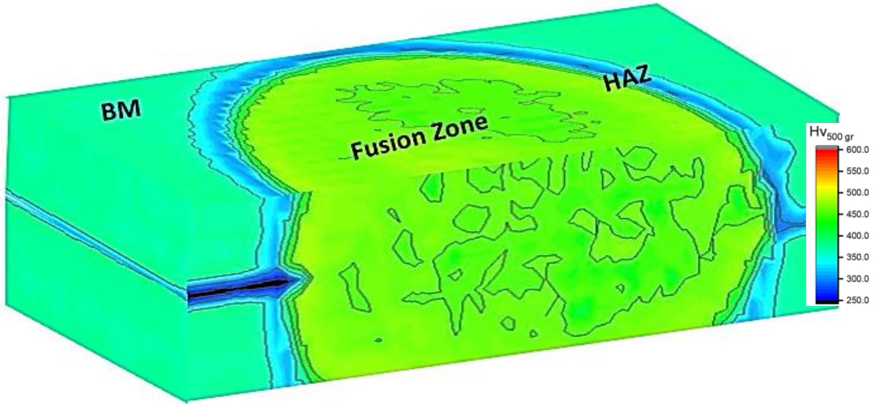
3G-980 Optimized Spot Weld (Nugget size of 7 mm)



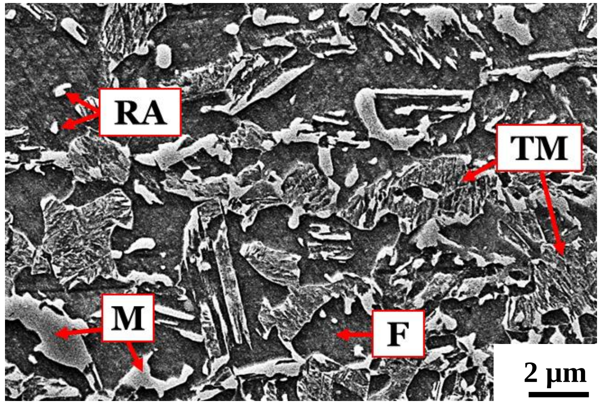
Weldability Lobes



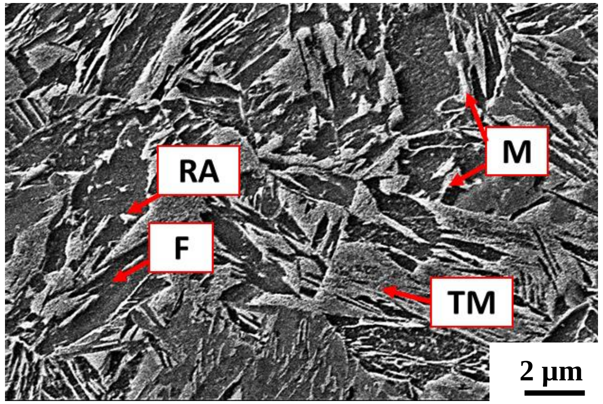
3G-1180 Optimized Spot Weld (Nugget size of 7 mm)



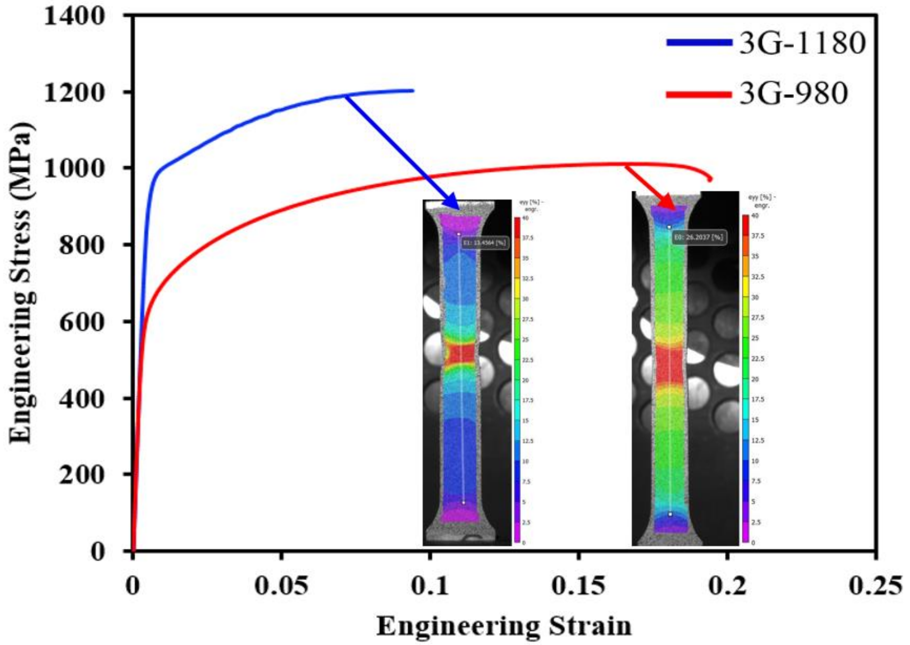
# Investigated Materials



3G-980 (uncoated)
1.4 mm thickness
Base material hardness:
300 ± 6 HV



3G-1180 (uncoated)
1.4 mm thickness
Base material hardness:
380 ± 5 HV

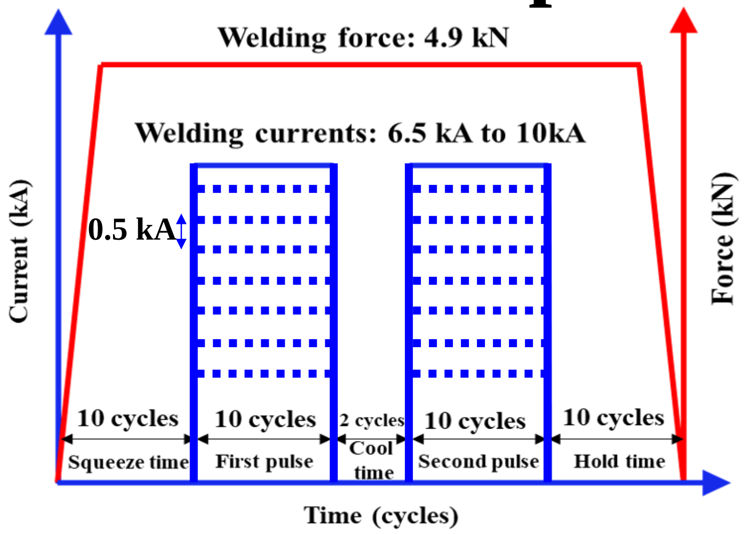


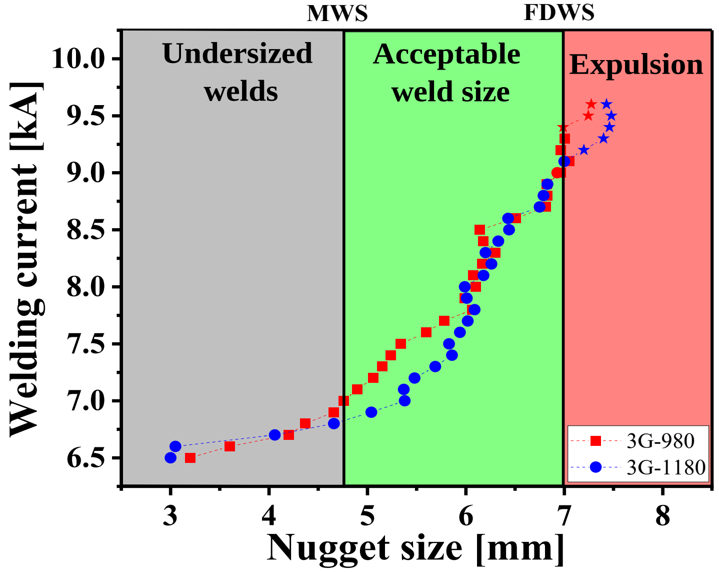
| Material | C | Mn | Si | Cr+Mo+V | Cu+Ni | $C_{eq}$ |
|---|---|---|---|---|---|---|
| 3G-980 | 0.21 | 2.11 | 1.49 | 0.02 | <0.01 | 0.64 |
| 3G-1180 | 0.17 | 2.52 | 1.59 | 0.28 | <0.02 | 0.70 |

| Material | Sheet Thickness [mm] | YS [MPa] | UTS [MPa] | TE [%] | UE [%] |
|---|---|---|---|---|---|
| 3G-980 | 1.4 | 605 ± 7.78 | 1002 ± 8.29 | 19.89 ± 0.50 | 16.8 ± 0.55 |
| 3G-1180 | 1.4 | 967 ± 7.05 | 1181 ± 19.02 | 11.83 ± 0.6 | 8.1 ± 0.35 |

YS, yield strength; UTS, ultimate tensile strength; TE, total elongation; UE, uniform elongation; 0.2% offset method was used to calculate YS

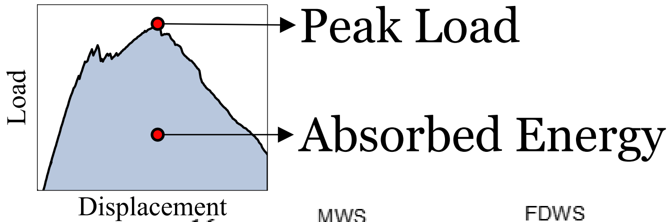
# RSW Process Optimization

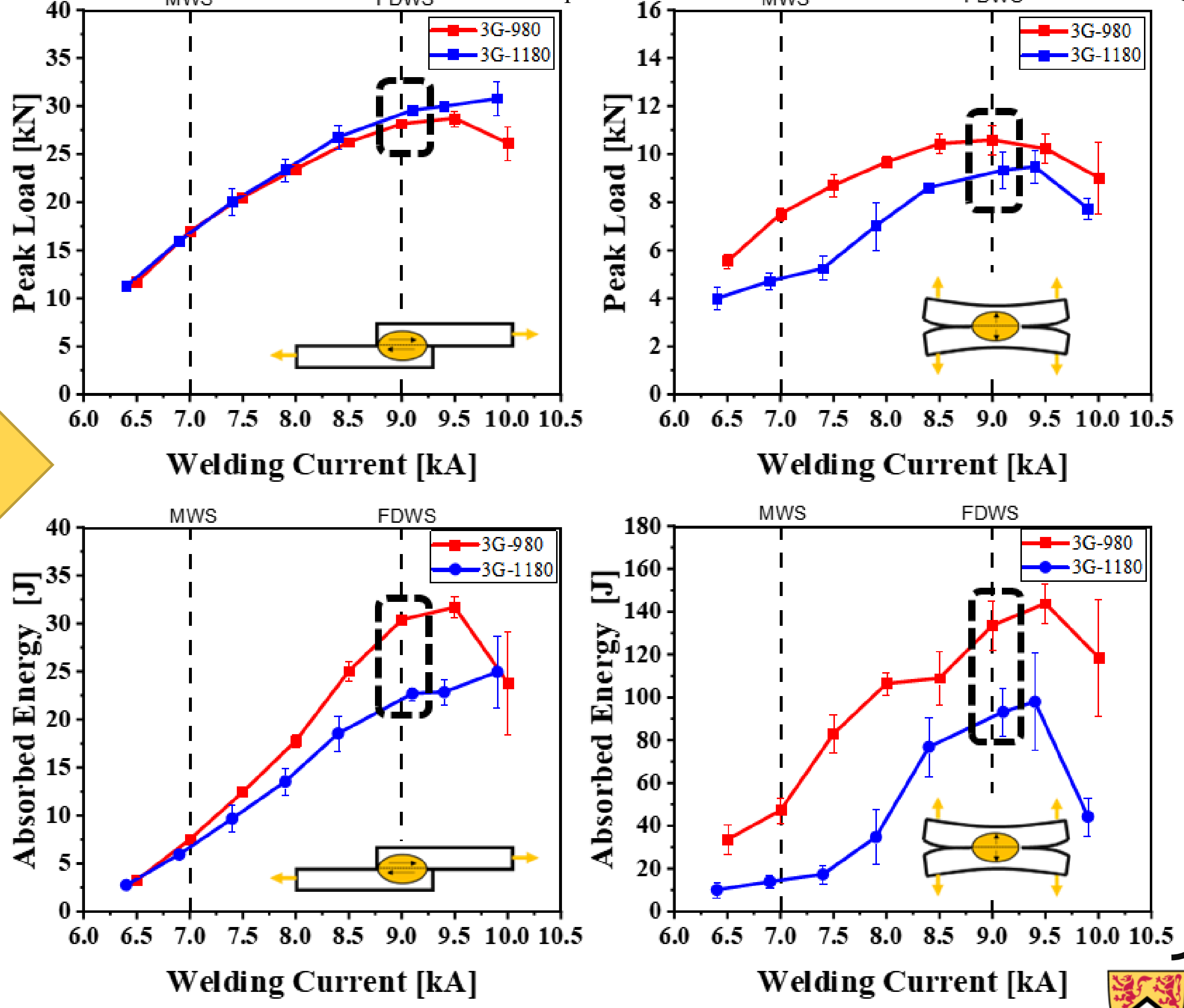




FDWS: Electrode Face Diameter Weld Size (≈ 7 mm)

MWS: Minimum Weld Size (4√t ≈ 4.8 mm)





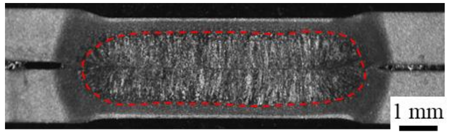
Optimized Welding Currents Based on AWS recommendations

**9.1 kA for 3G-980**

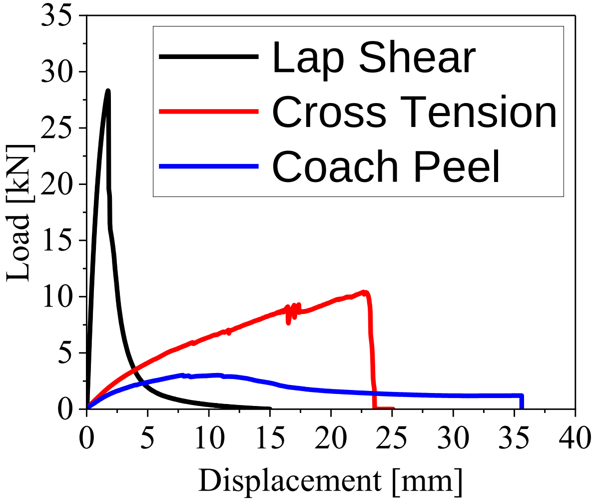
**9.0 kA for 3G-1180**

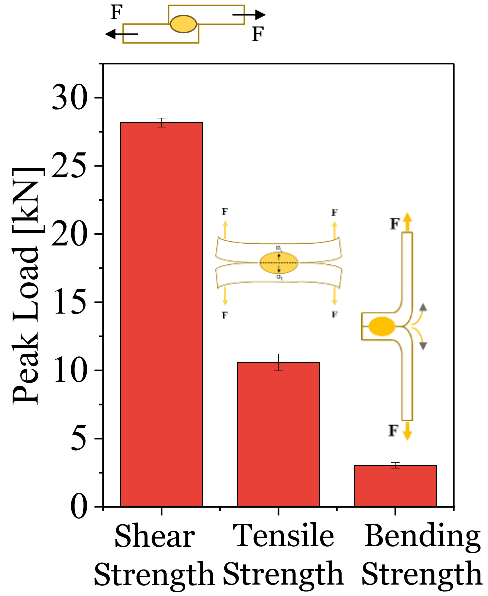
# Seeger's Nominal Failure Surfaces:

3G-980 FDWS

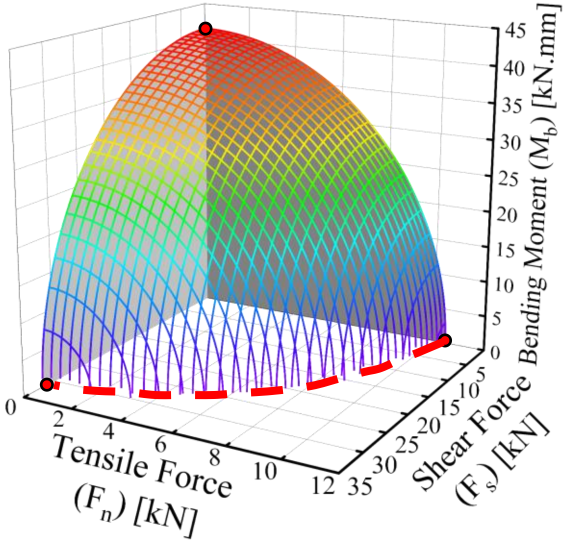


**(nugget diameter: 7.0 ± 0.1 mm)**

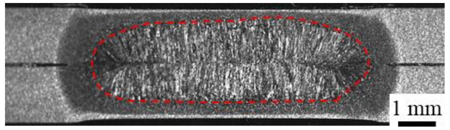




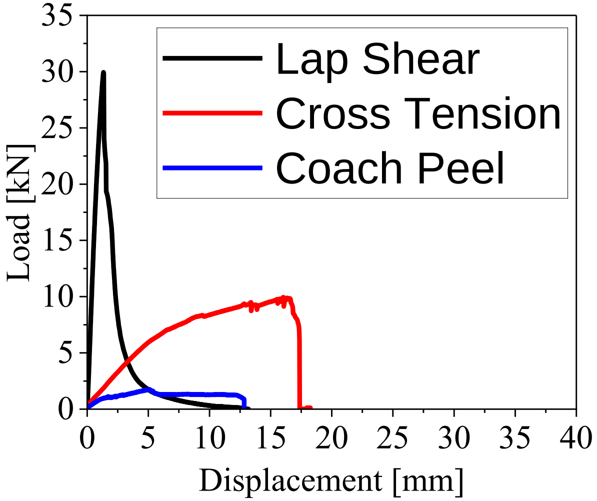
$$f^{Seeger} = \left\{\left(\frac{f_s}{29.429}\right)^2+\left(\frac{f_n}{10.324}\right)^2 + \left(\frac{b_m}{41.407}\right)^2\right\}=1$$

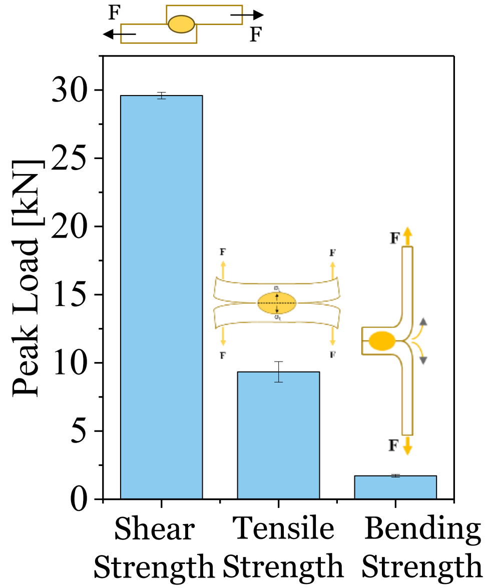


3G-1180 FDWS

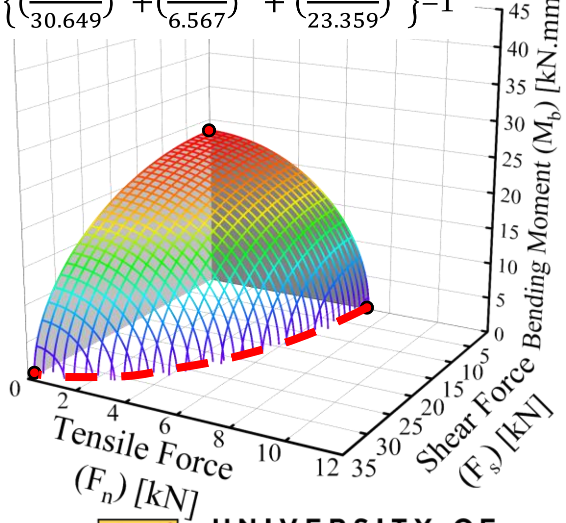


**(nugget diameter: 7.0 ± 0.2 mm)**



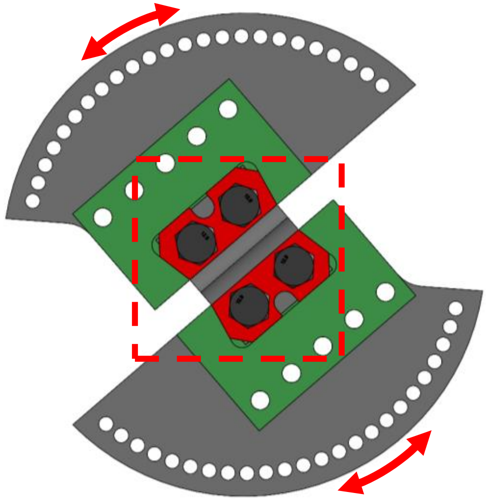


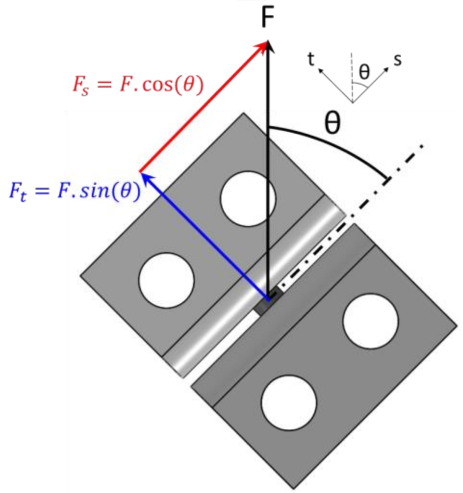
$$f^{Seeger} = \left\{\left(\frac{f_s}{30.649}\right)^2+\left(\frac{f_n}{6.567}\right)^2 + \left(\frac{b_m}{23.359}\right)^2\right\}=1$$

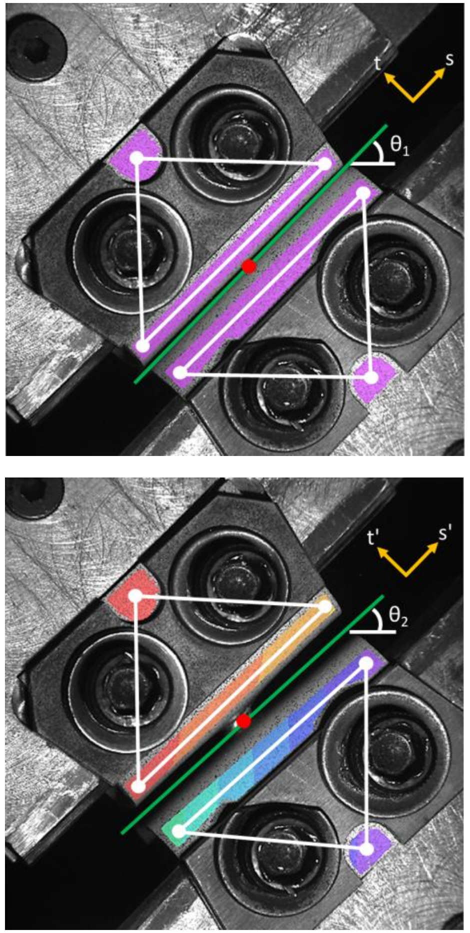


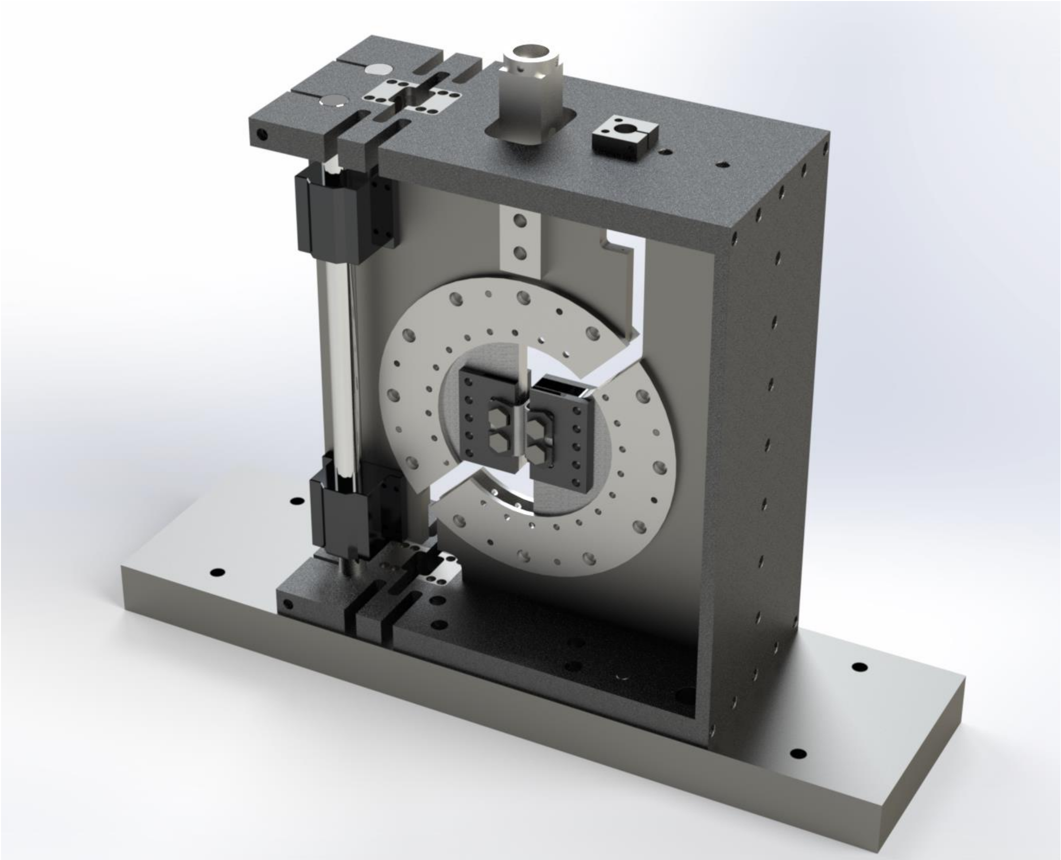
# Task 2

# Mechanical Performance of Spot Welds Under Shear-tensile Loading Condition: The KS-II Test

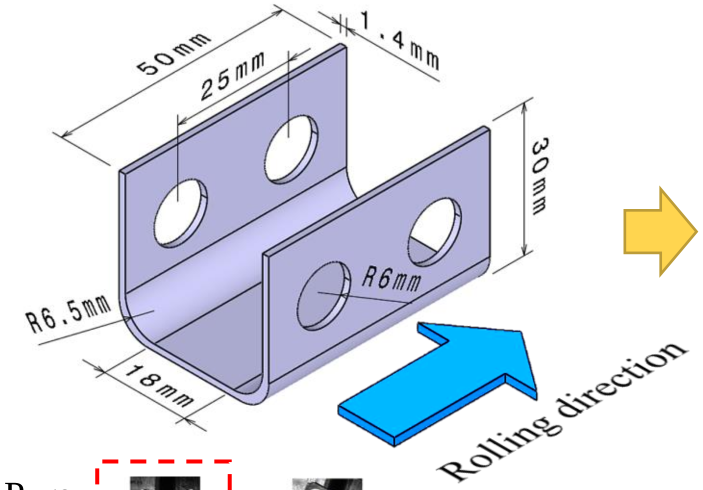


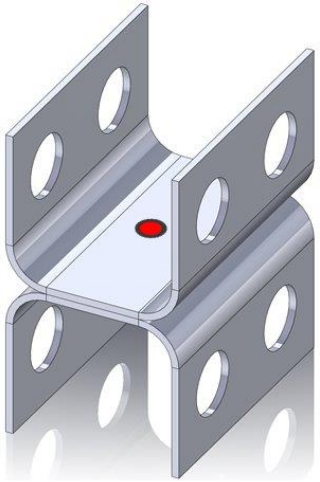


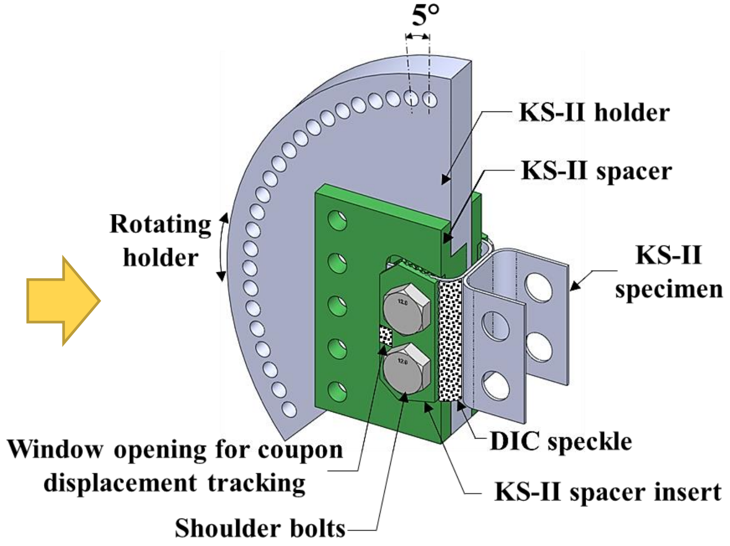


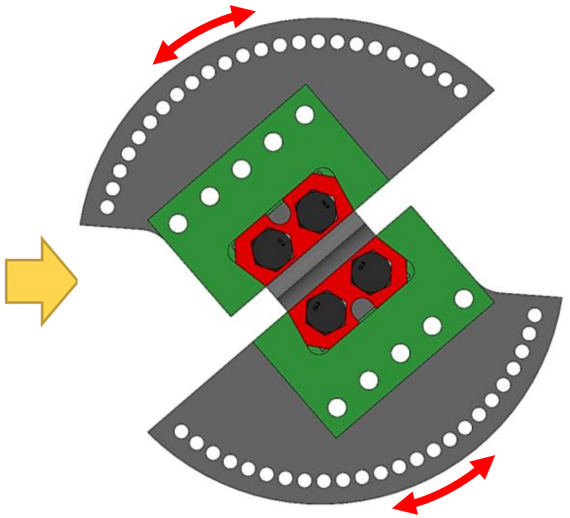


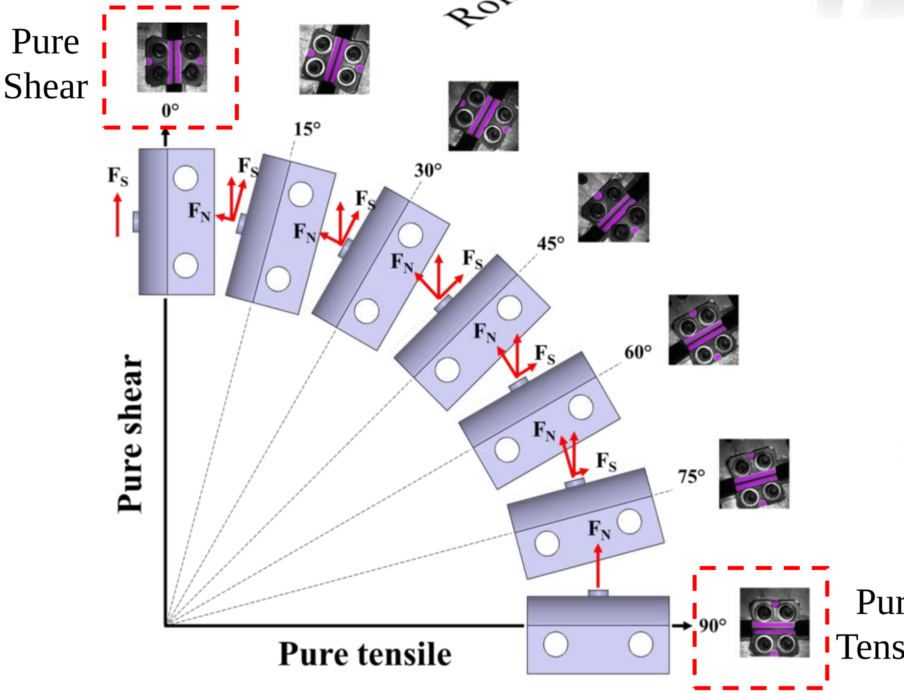
# Combined Shear-tensile Loading Methodology: The KS-II Test

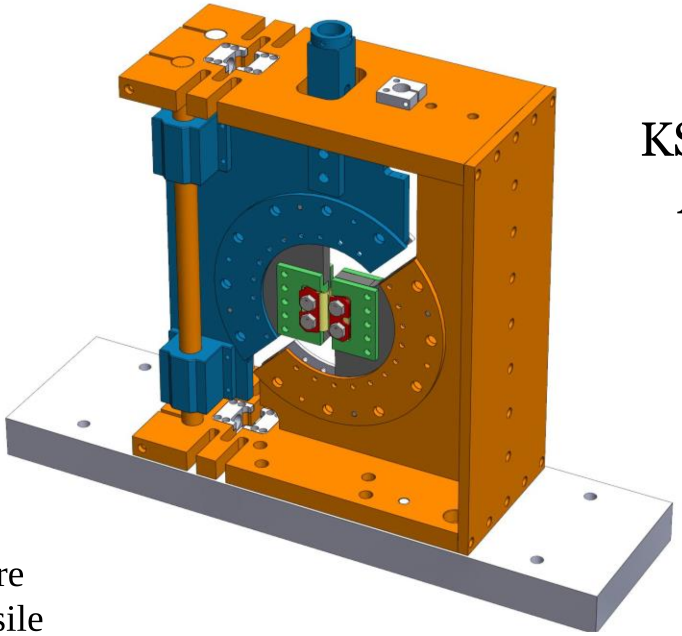


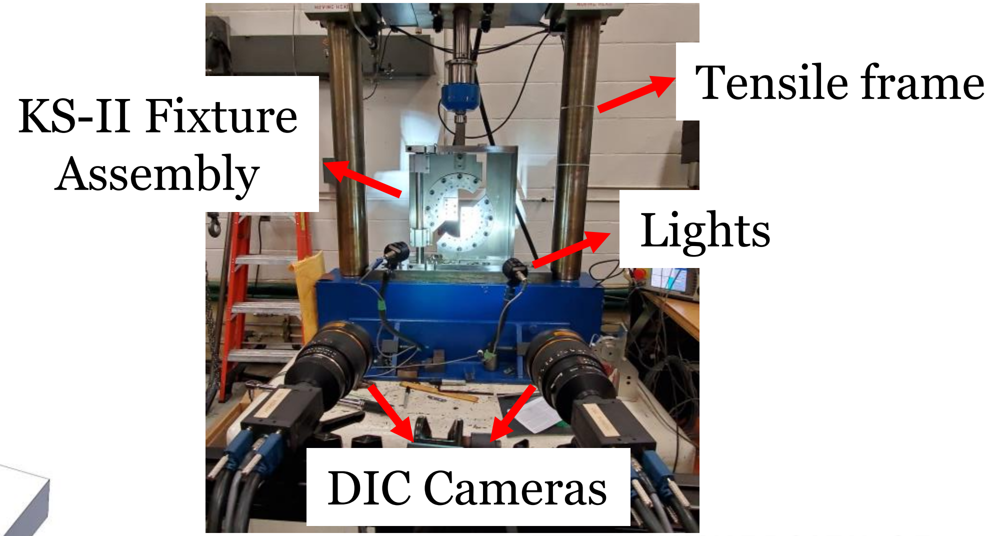






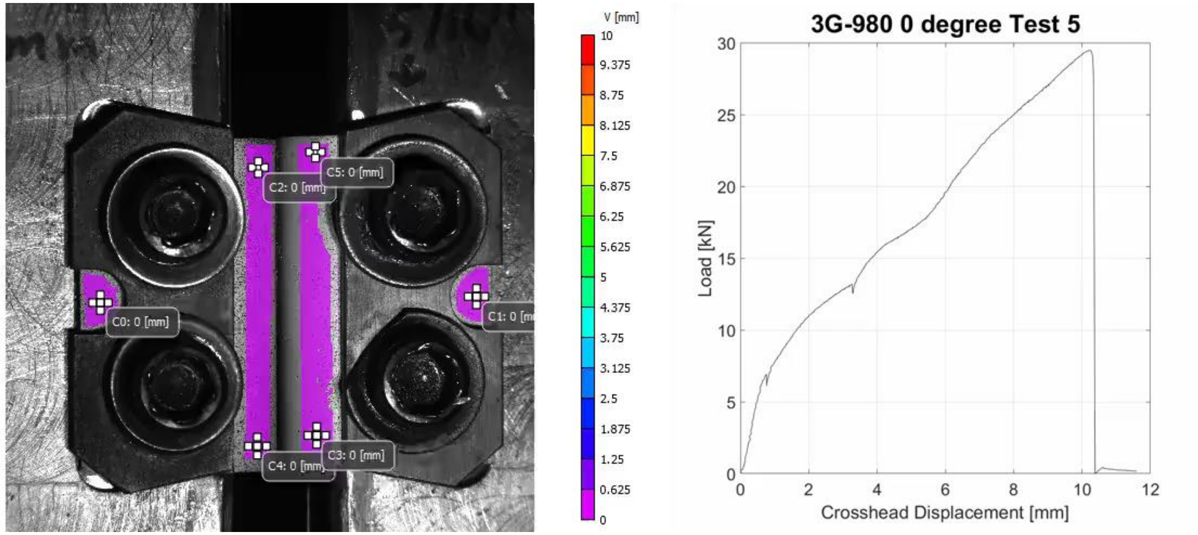




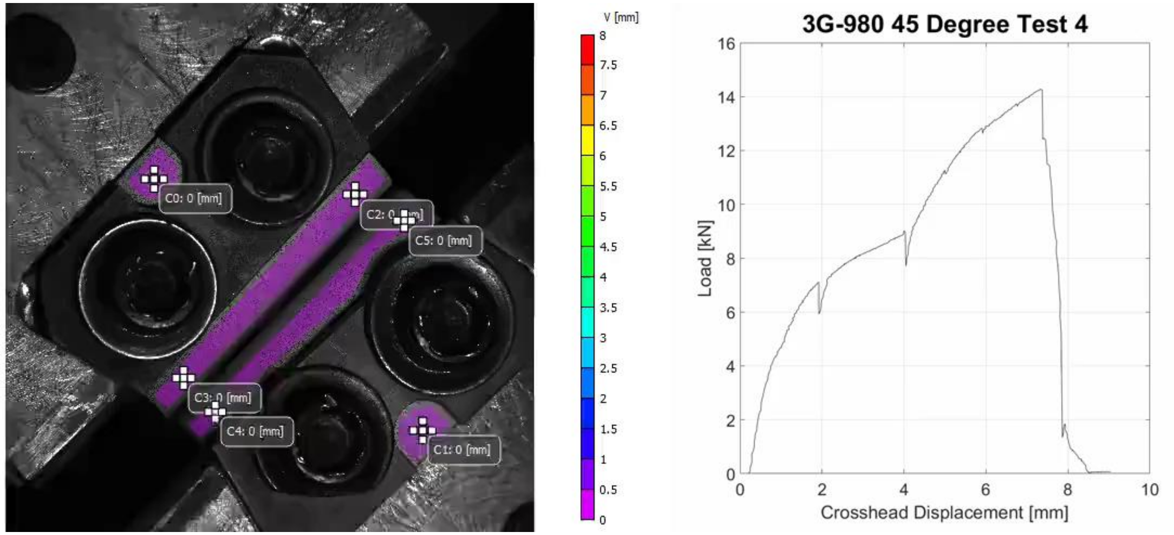


# Coupon Rotation and Slippage During KS-II Tests:

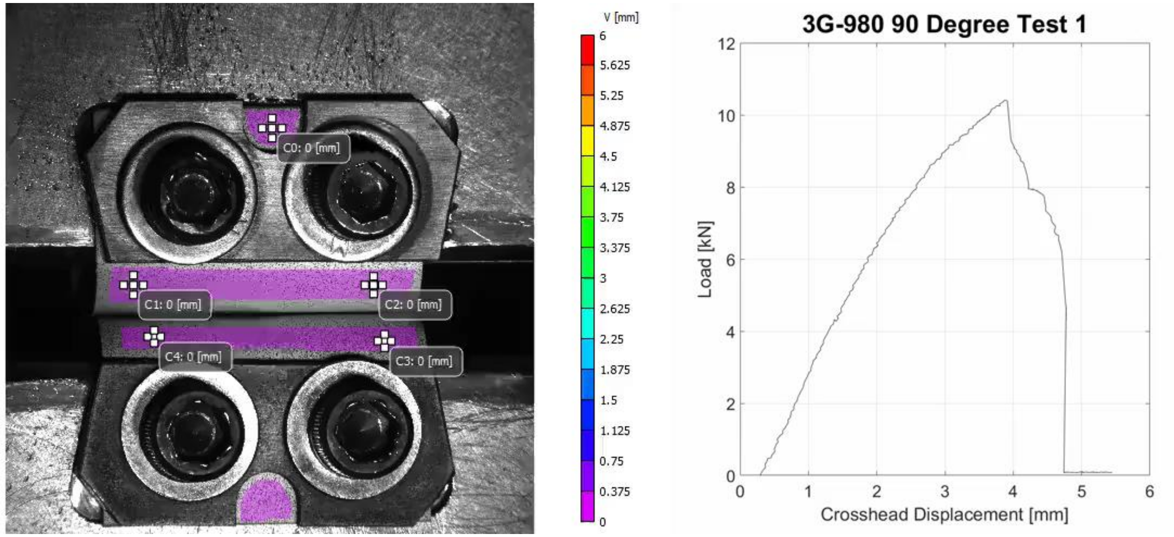
### 3G-980 KS-II 0° (Pure shear)



### 3G-980 KS-II 45°



### 3G-980 KS-II 90° (Pure tensile)

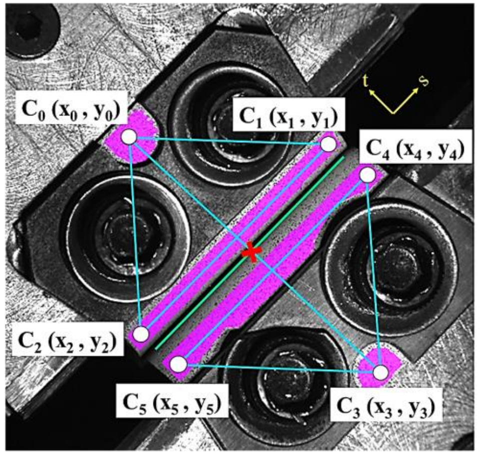


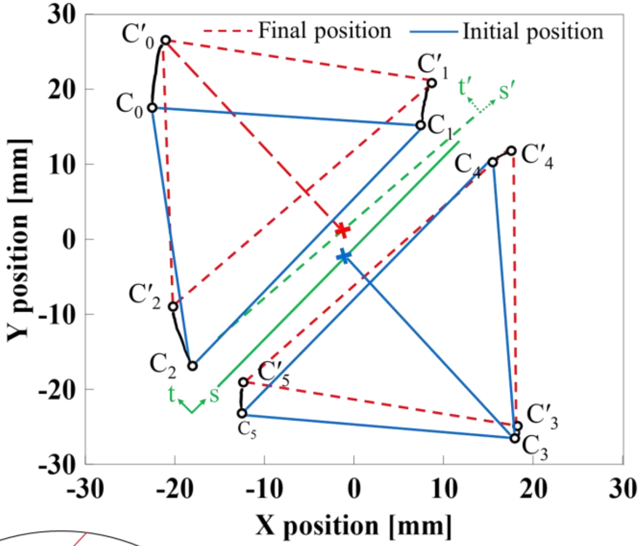
Slippage and rotation of the KS-II coupons were **noticeable** in **shear-dominated** loading orientations

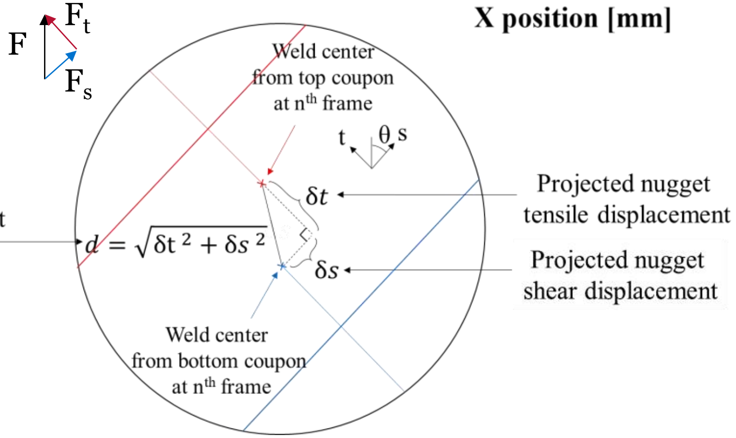
Slippage and rotation of the KS-II coupons were **negligible** in **tensile-dominated** loading orientations

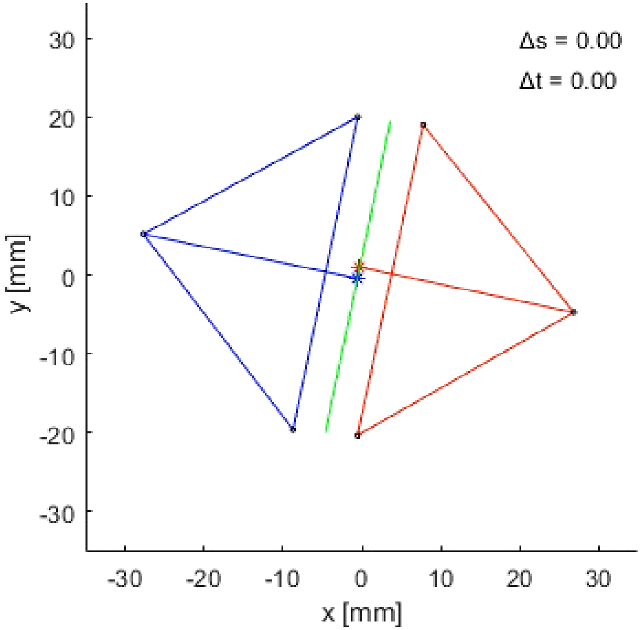
# Developed Triangulation Method:

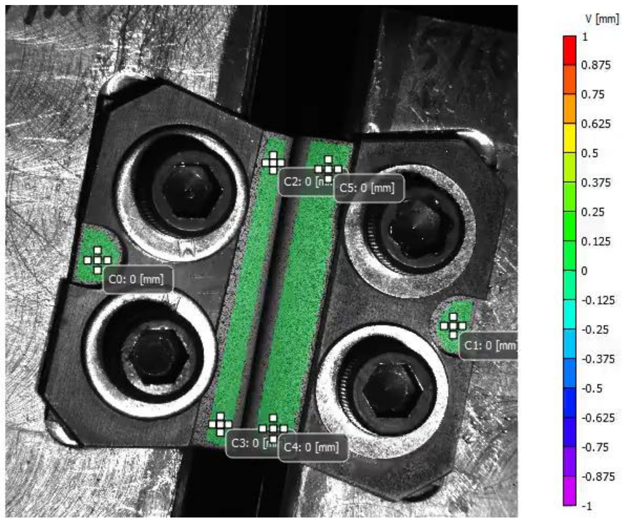
Instantaneous tracking of nugget orientation

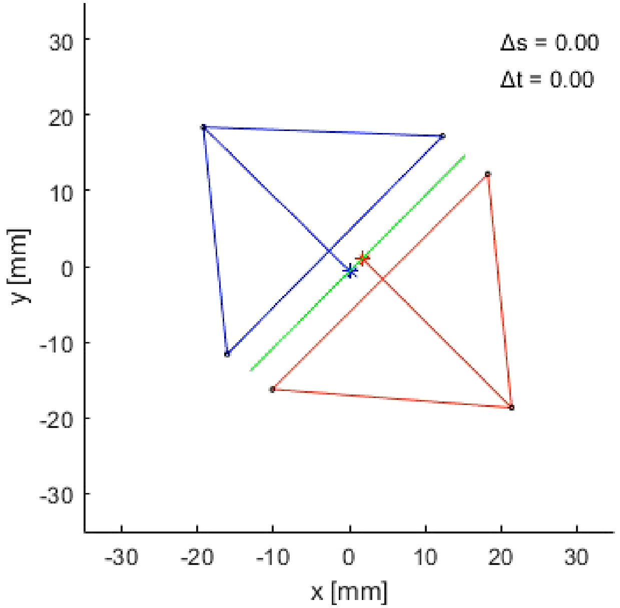


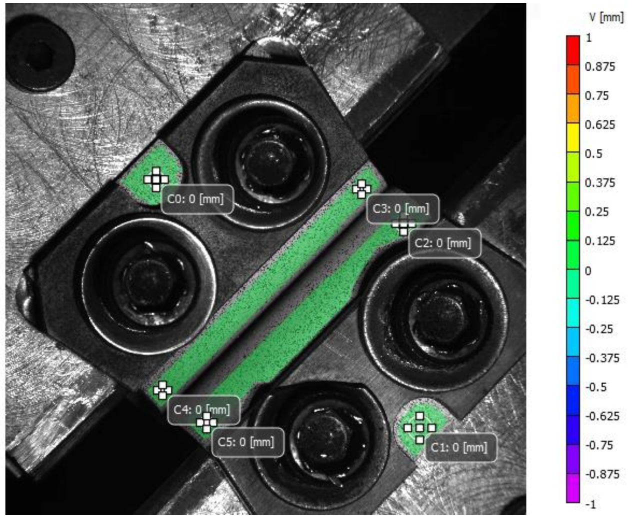




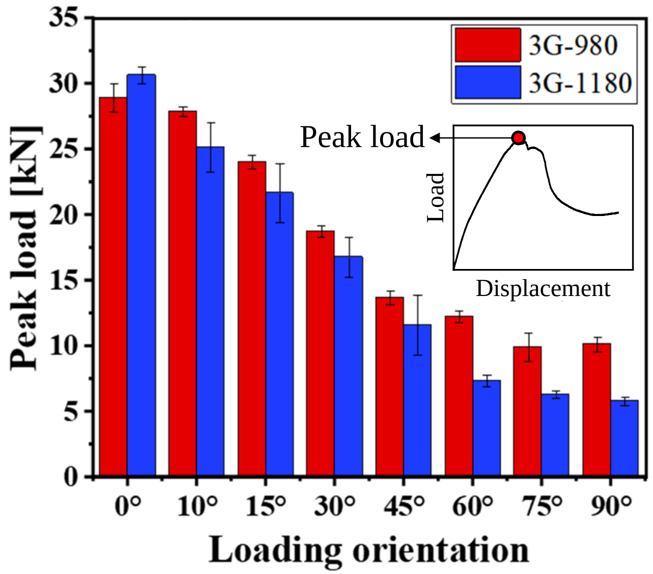


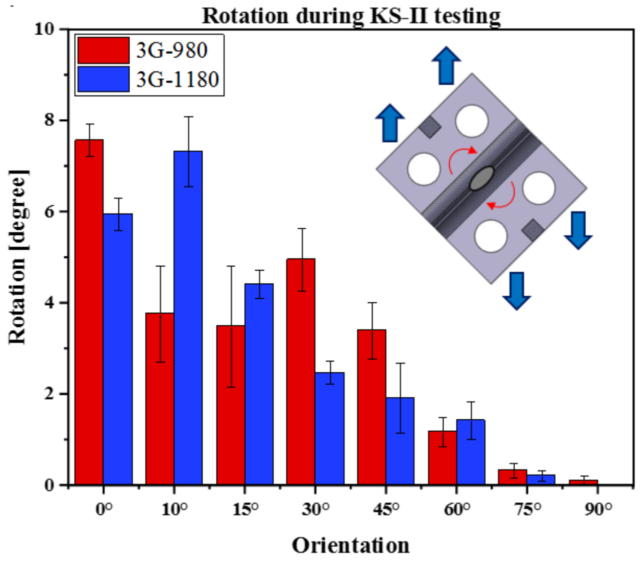




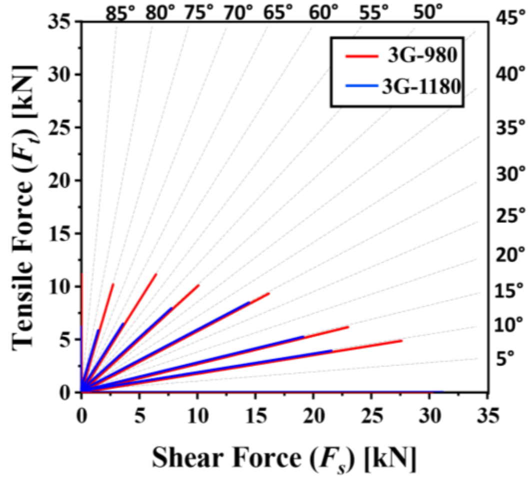


# Shear-tensile Failure Loci:

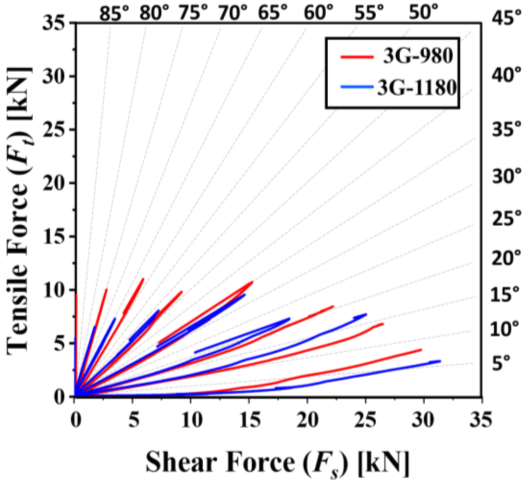




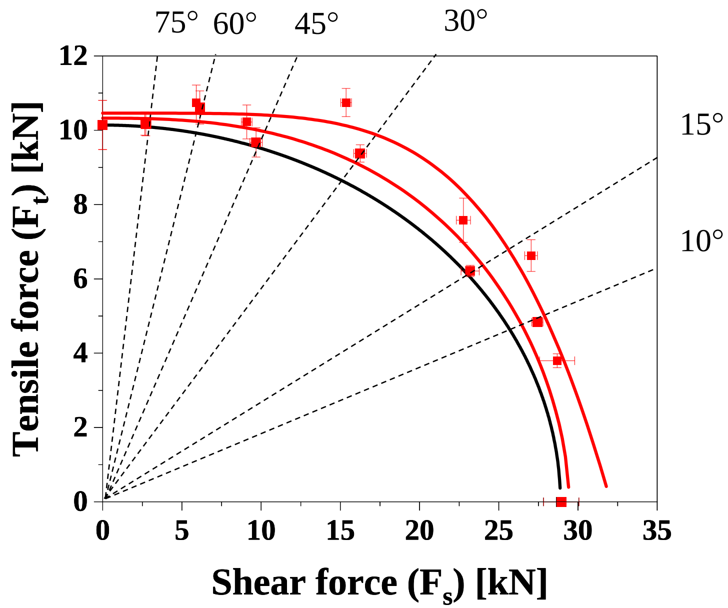
Nominal ratio $F_{shear}/F_{tensile}$



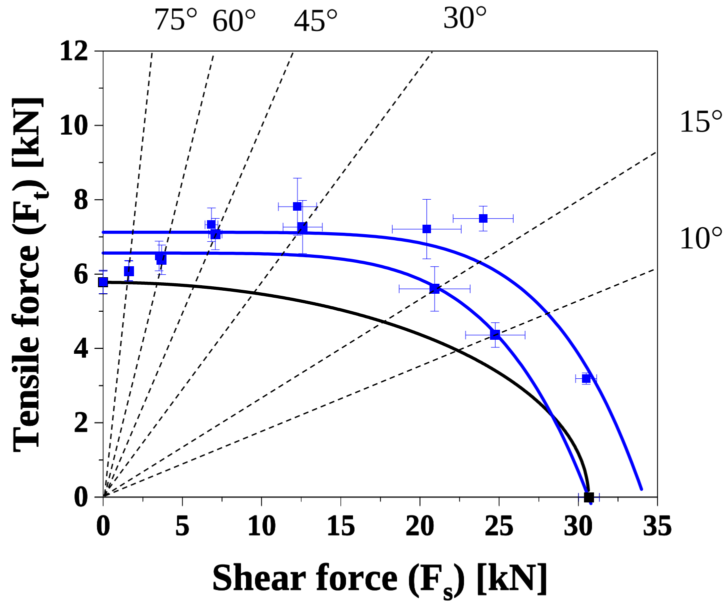
Final ratio $F_{shear}/F_{tensile}$



3G-980



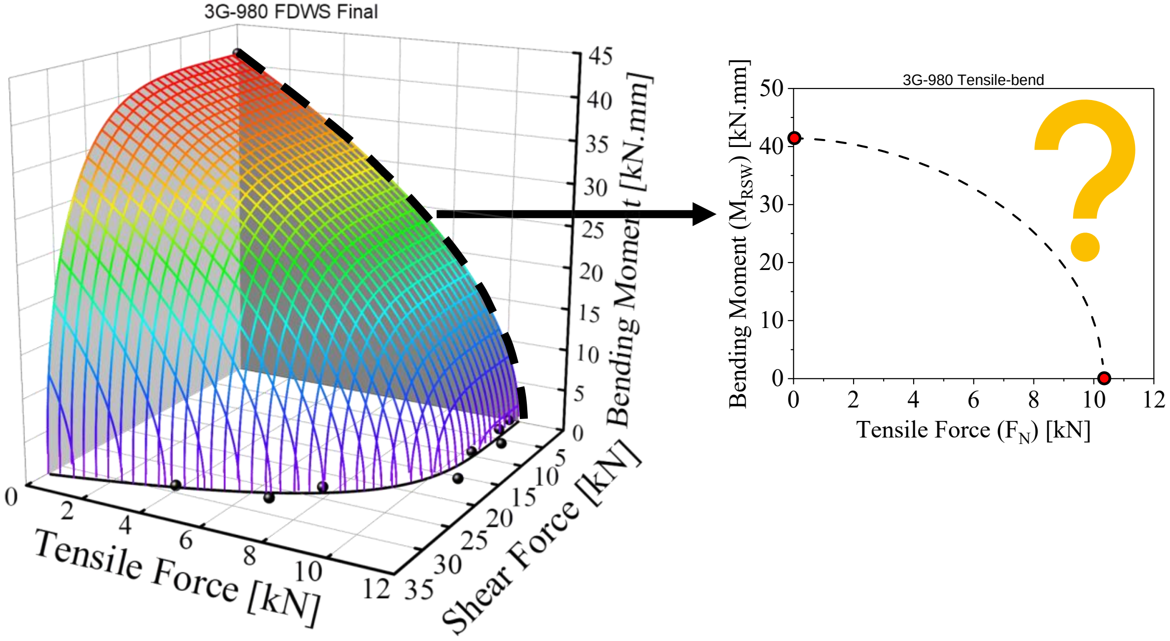
3G-1180



# Updated Failure Surface:

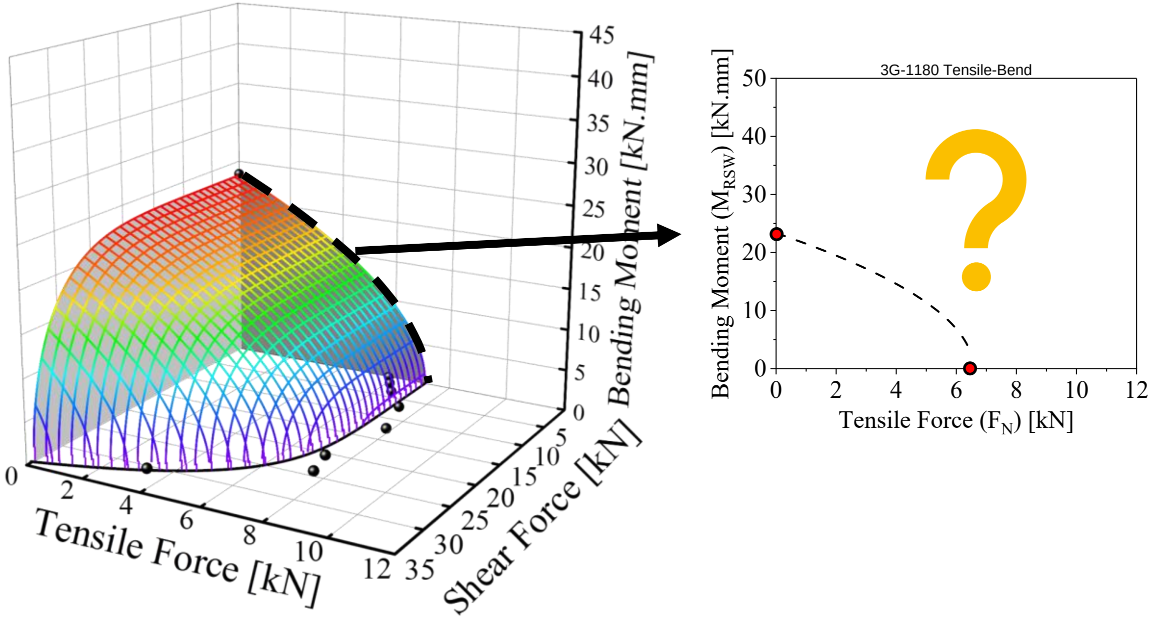
## 3G-980 FDWS

$$f^{Seeger}=\left\{\left(\frac{f_s}{29.429}\right)^{2.616}+\left(\frac{f_n}{10.324}\right)^{1.819}+\left(\frac{b_m}{41.407}\right)^{2}\right\}=1$$



## 3G-1180 FDWS

$$f^{Seeger}=\left\{\left(\frac{f_s}{30.649}\right)^{5.222}+\left(\frac{f_n}{6.567}\right)^{1.123}+\left(\frac{b_m}{23.359}\right)^{2}\right\}=1$$



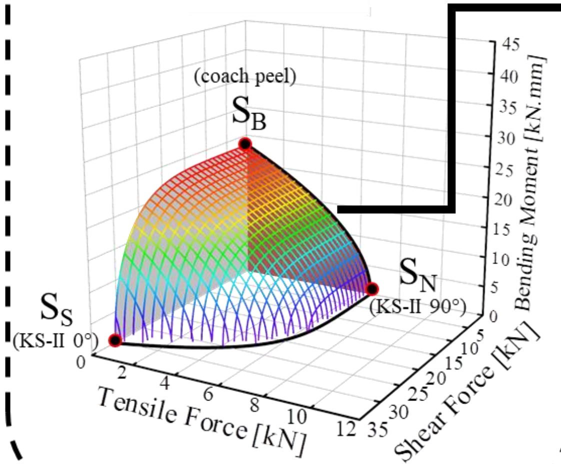
# Task 3

# Mechanical Performance of Spot Welds Under Tensile-bending Loading Condition: The Coach Peel Test

### Conventional Three-dimensional Failure Surface Development for 3G-AHSS Resistance Spot Welds

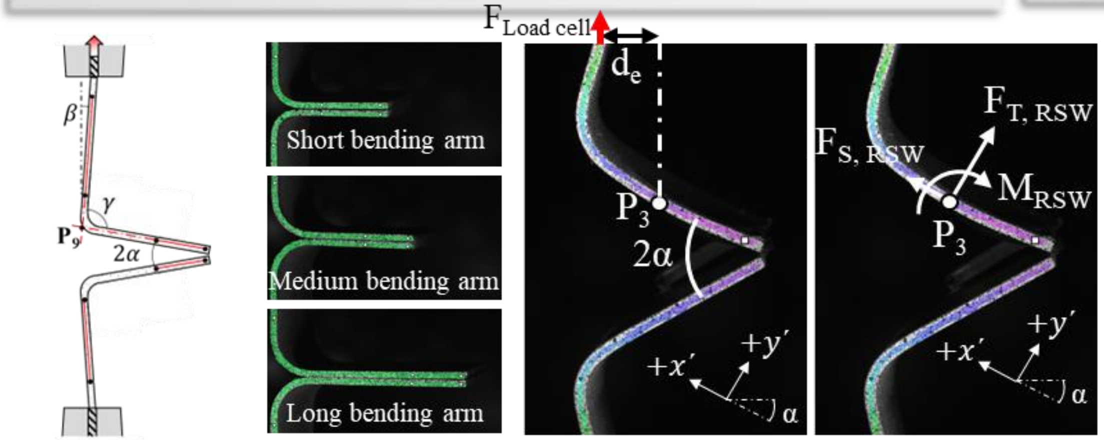
$$f = \left[\frac{F_s}{S_S}\right]^a + \left[\frac{F_n}{S_N}\right]^b + \left[\frac{M_b}{S_B}\right]^c \leq 1$$

Shear Strength | Tensile Strength | Bending Strength

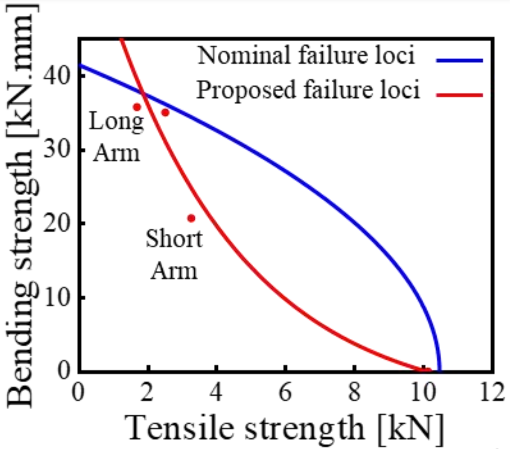


### Evaluating Failure Surface Predictions in Bending Dominated Loading Conditions

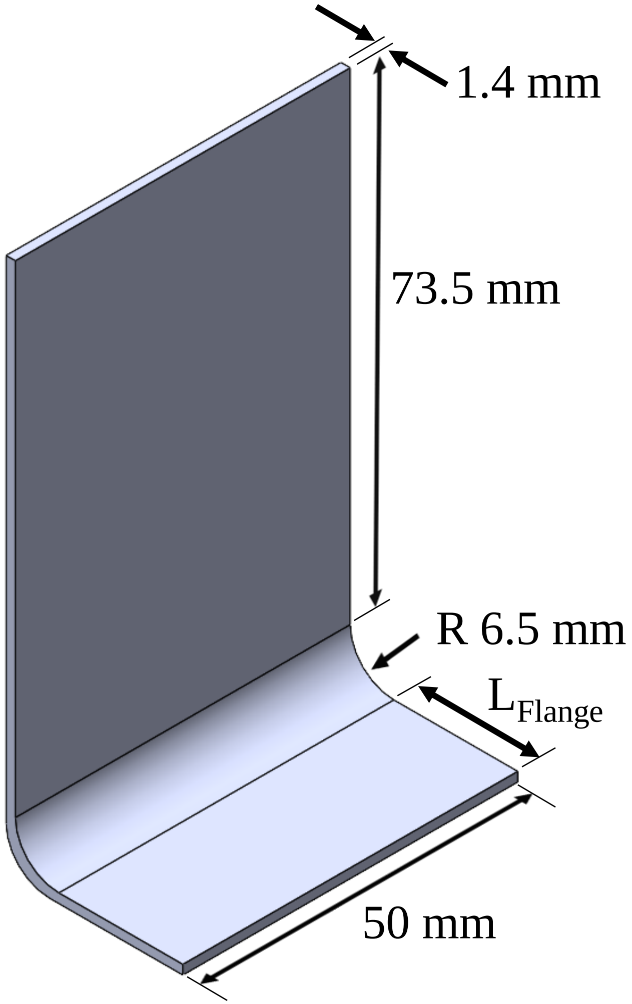
#### Tracking of Tensile Force and Bending Arm Evolution Using Different Coach Peel Geometries

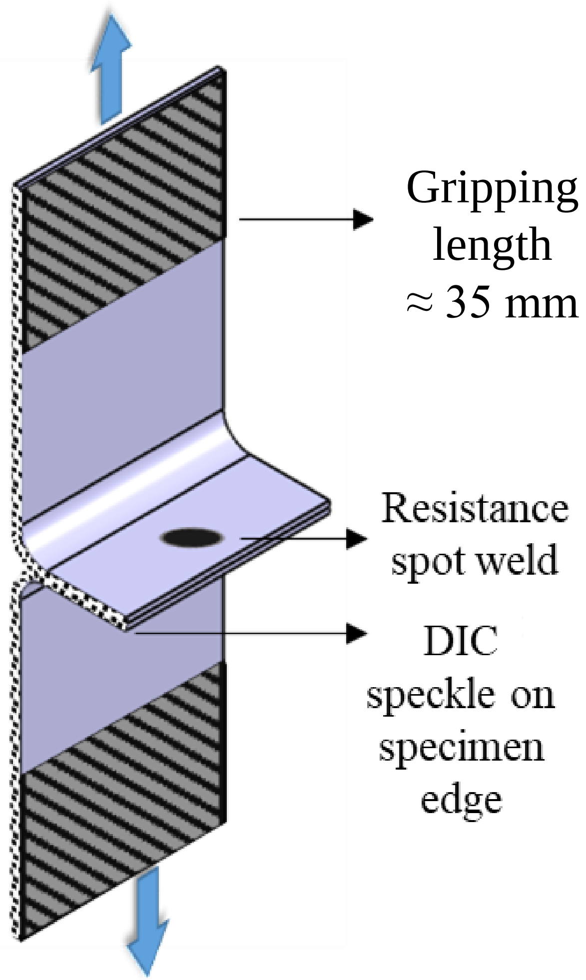


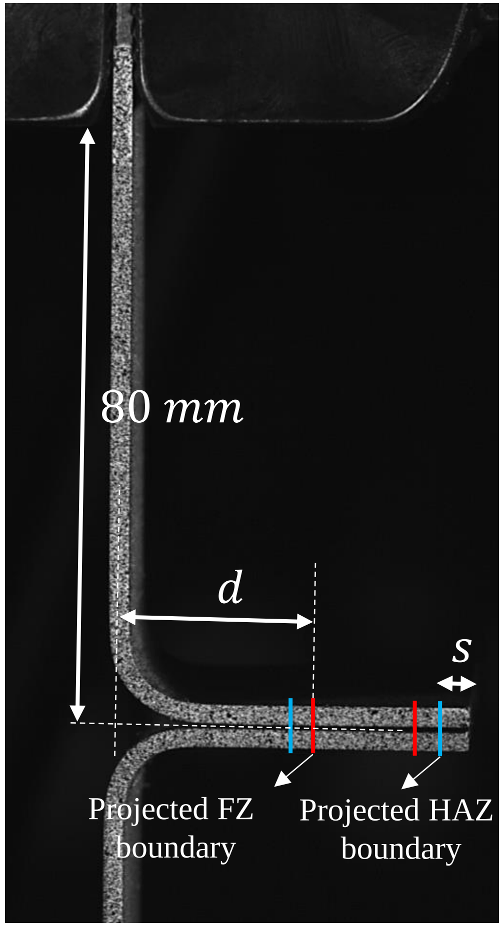
#### Improved Failure Locus Functional Form Proposed in Tensile-Bending Loading Plane

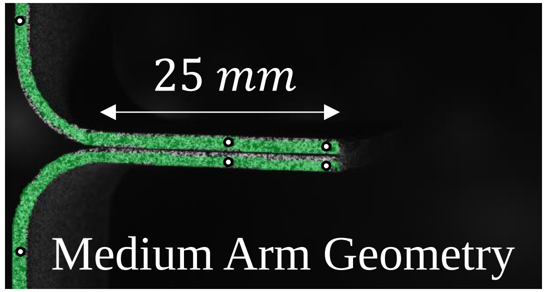


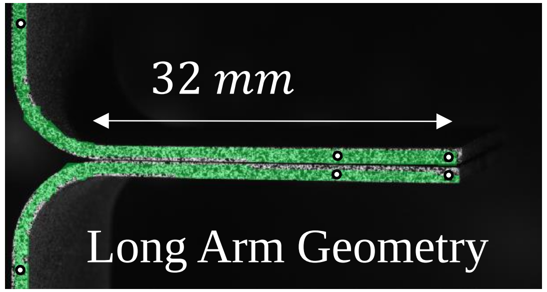
# Combined Tensile-bending Loading Methodology: The Coach Peel Test





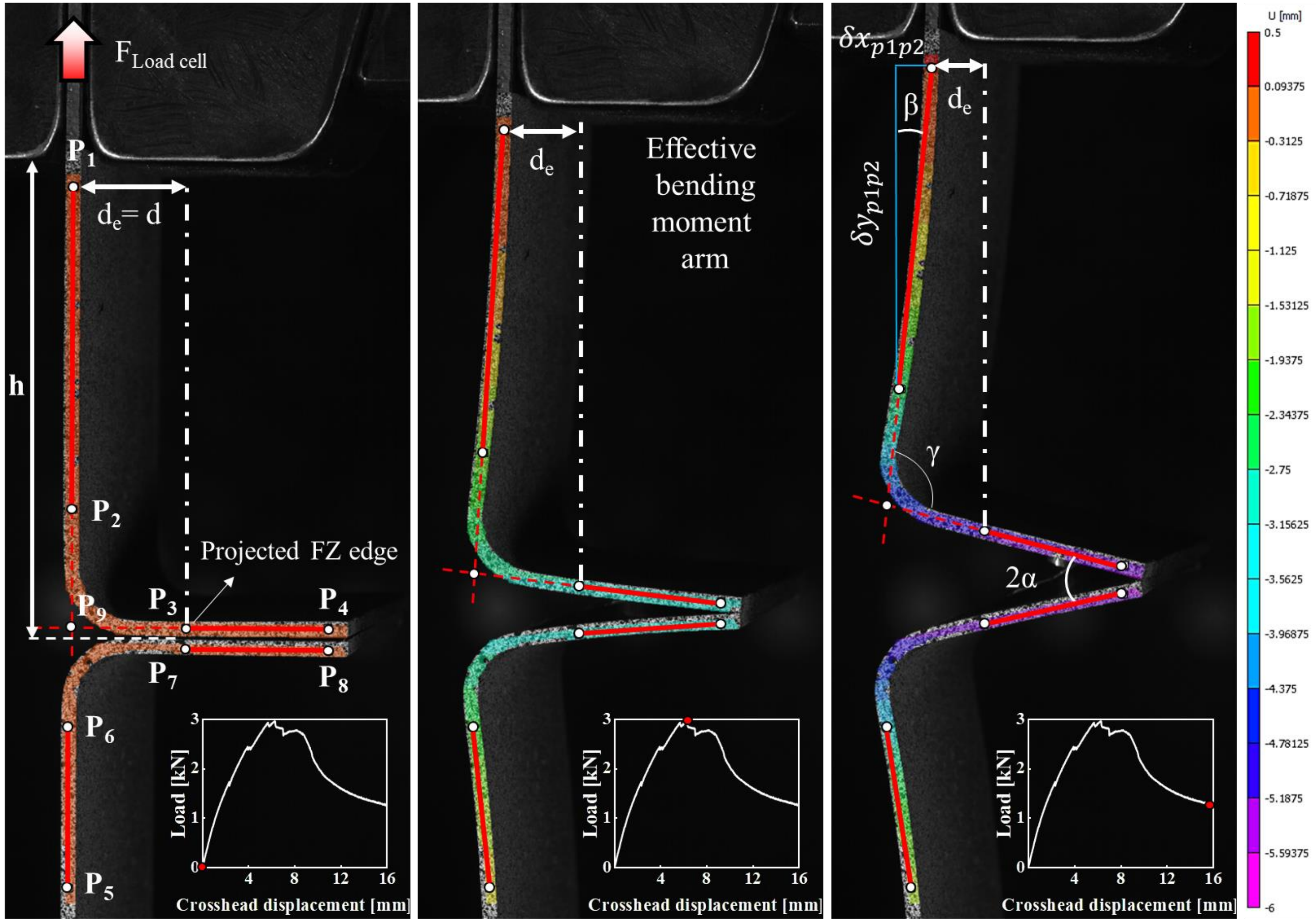






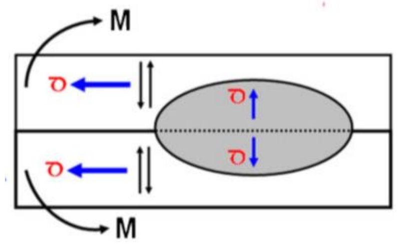
# An example of coupon deformation during coach peel tests:

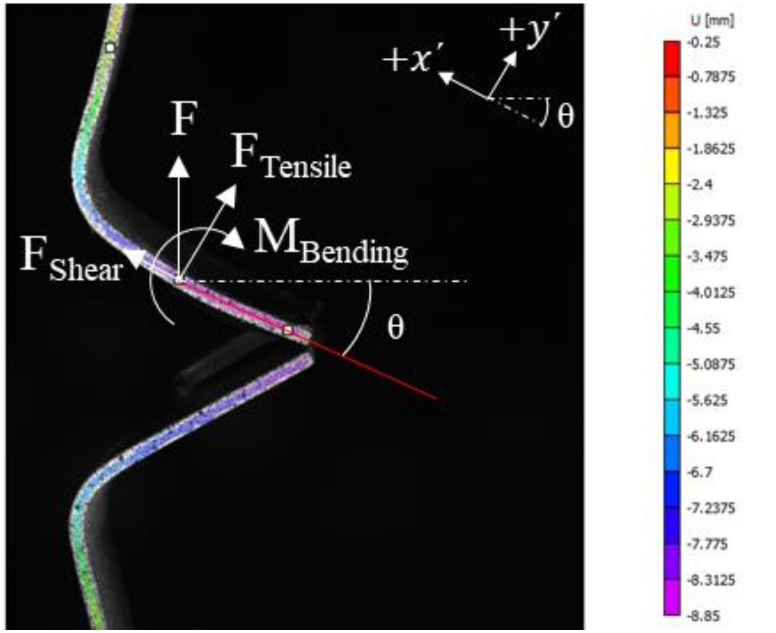
First frame | Peak load frame | Final frame



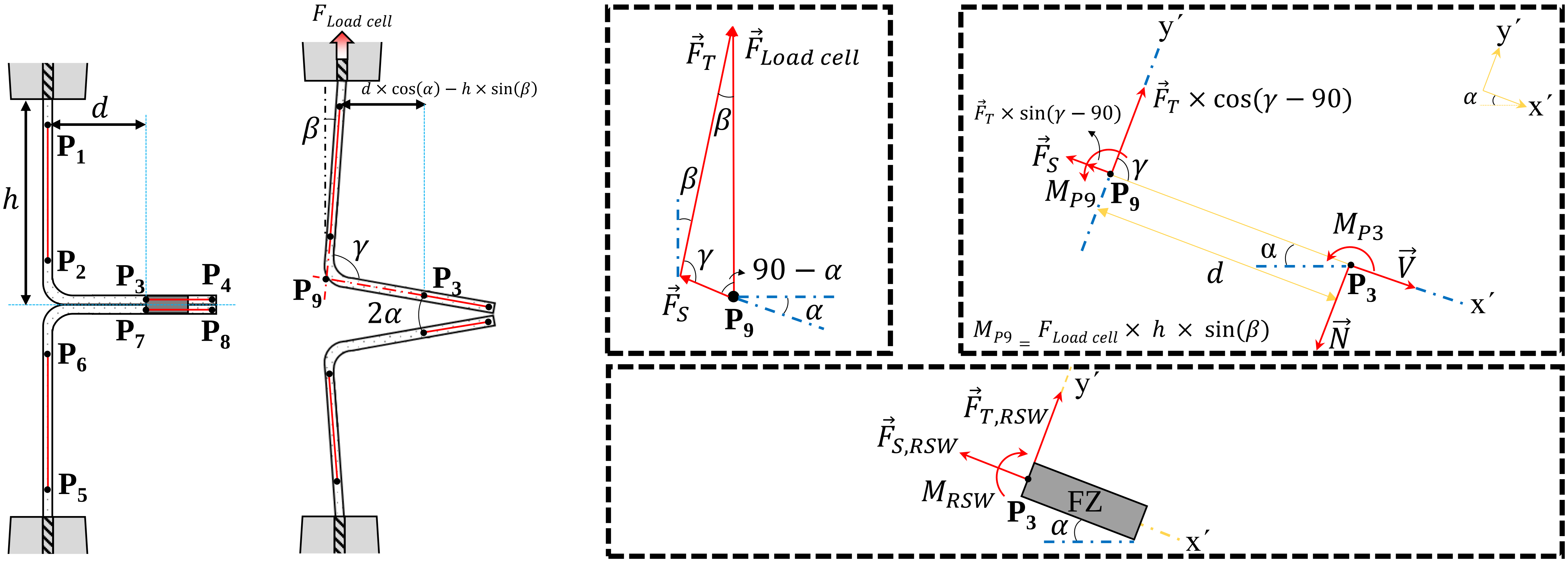
The evolution of the following loads/moments should be considered:

- Bending Moment
- Tensile Stress
- Transverse Shear Stress





# Static force equilibrium analysis on coach peel coupons:



**Shear force**

$$|\vec{F}_{S,RSW}| = |\vec{V}| = \frac{|\vec{F}_{Load\ cell}|}{\sin(\gamma)}[\sin(\beta) - \cos(\alpha)\cos(\gamma)]$$

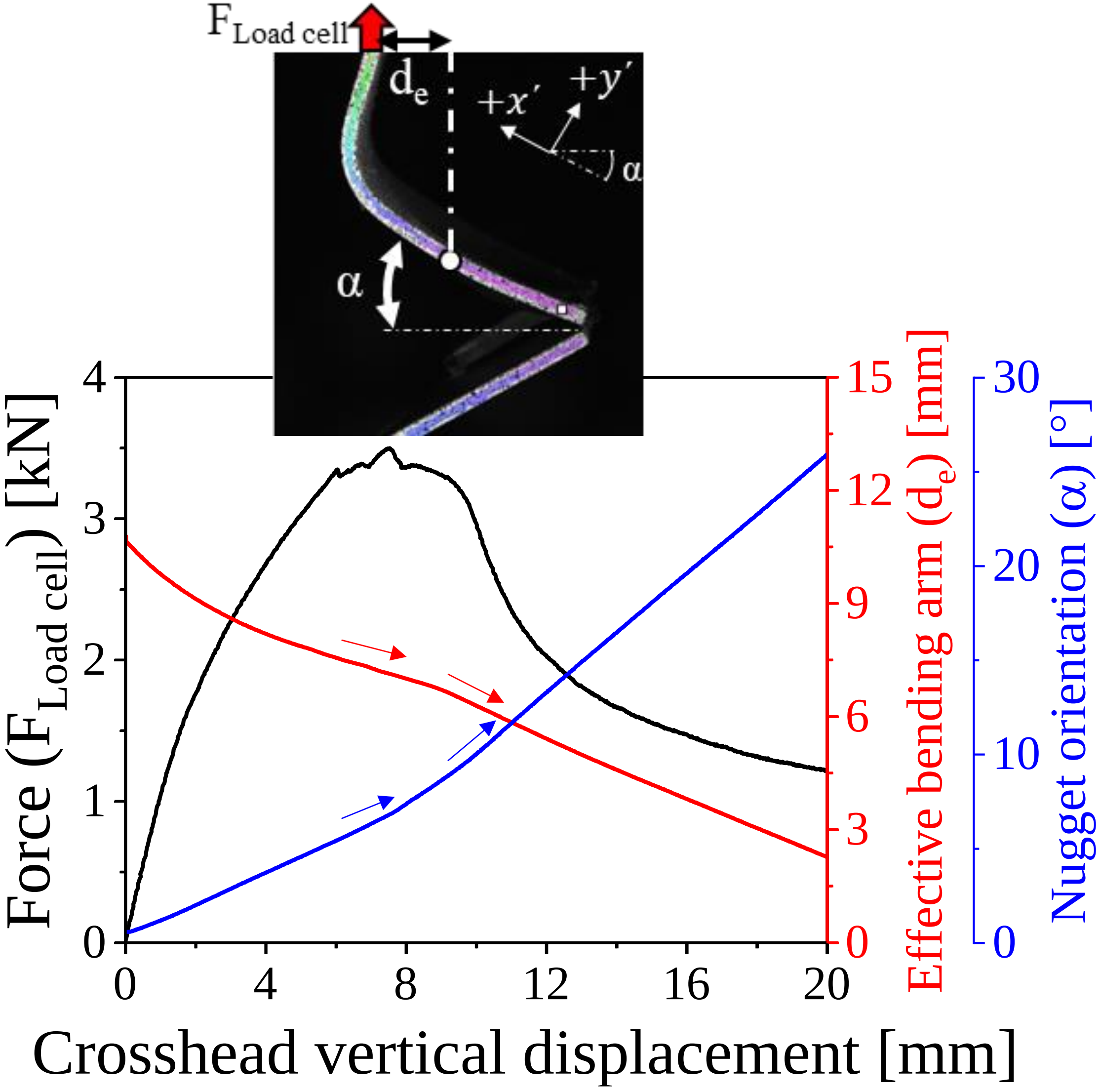
**Tensile force**

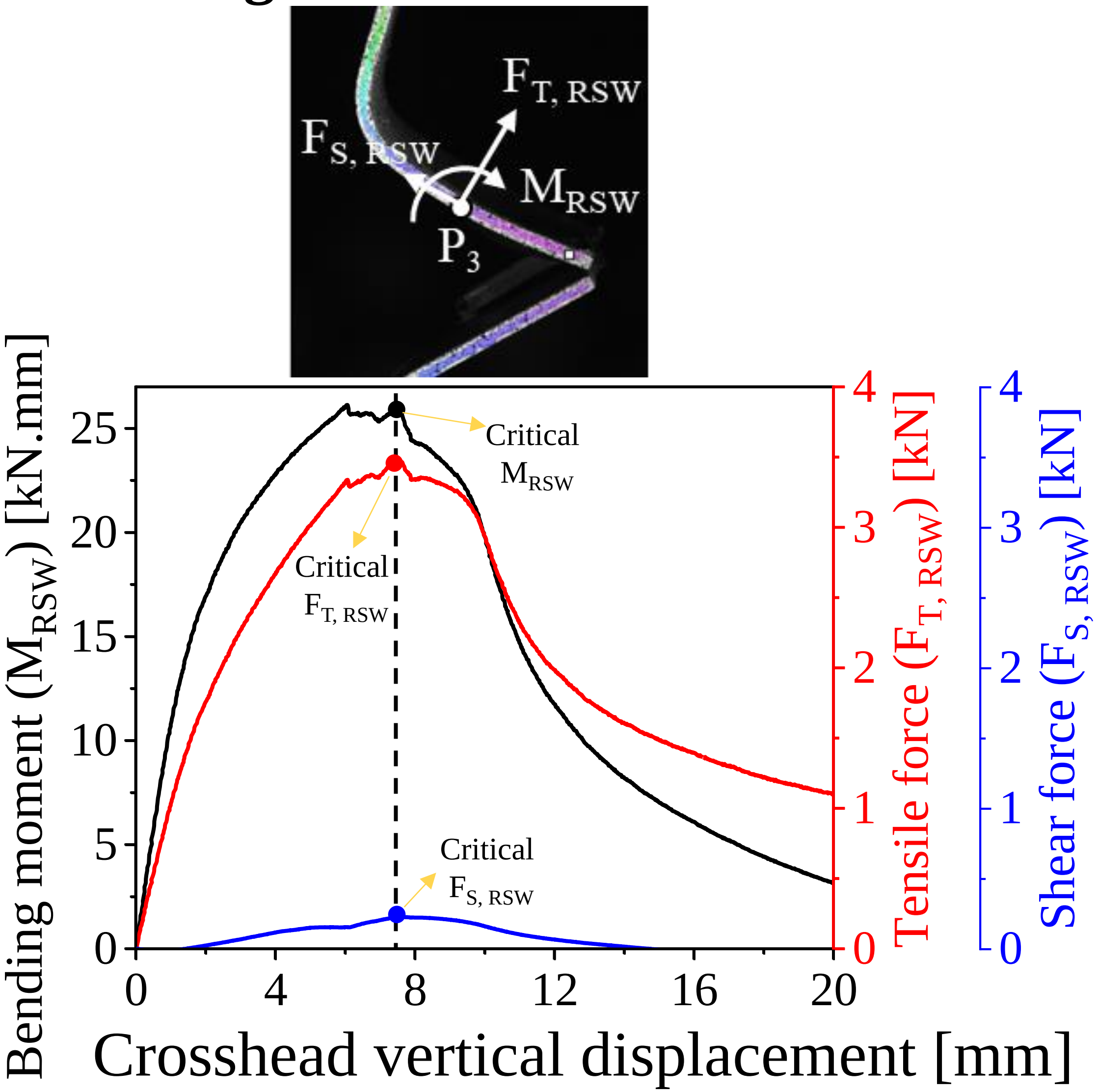
$$|\vec{F}_{T,RSW}| = |\vec{N}| = |\vec{F}_{Load\ cell}|\cos(\alpha)$$

**Bending moment**

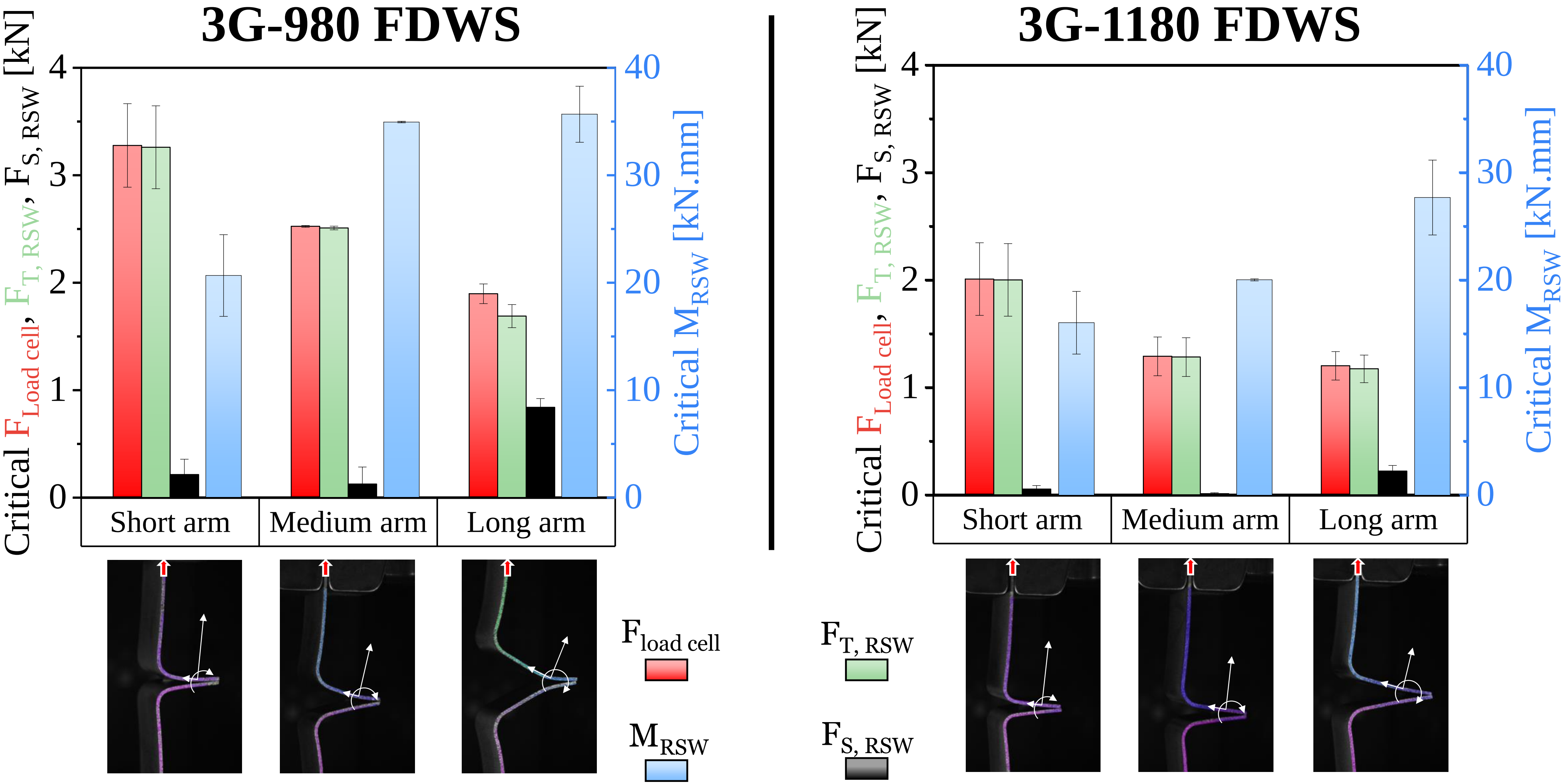
$$M_{RSW} = |\vec{F}_{Load\ cell}| \times [d \times cos(\alpha) - h \times sin(\beta)]$$

# Evolution of force components and bending moment during a CP test:



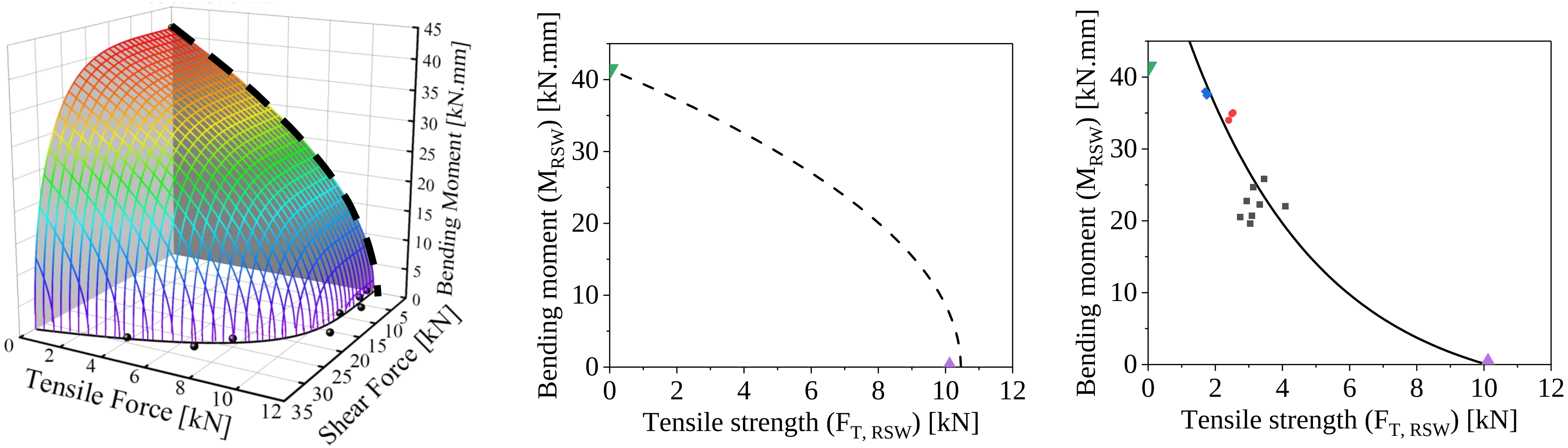


# Summary of critical loads/moments at the onset of failure during coach peel tests:

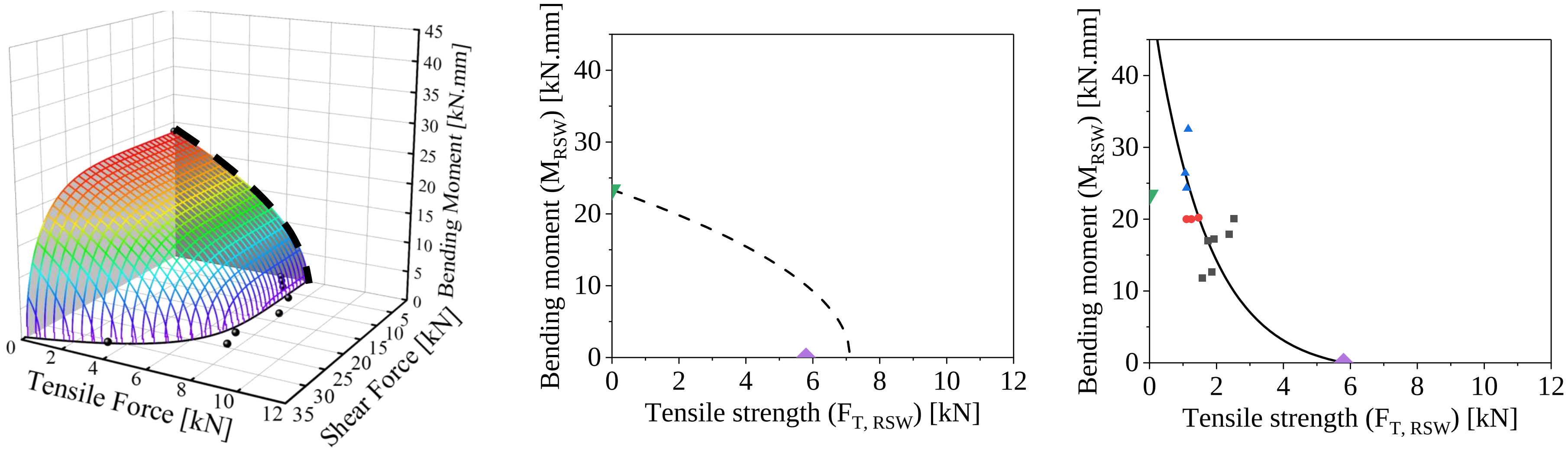


# Assessing Seeger’s Failure Loci in Tensile-bending Loading:

**3G-980**



**3G-1180**

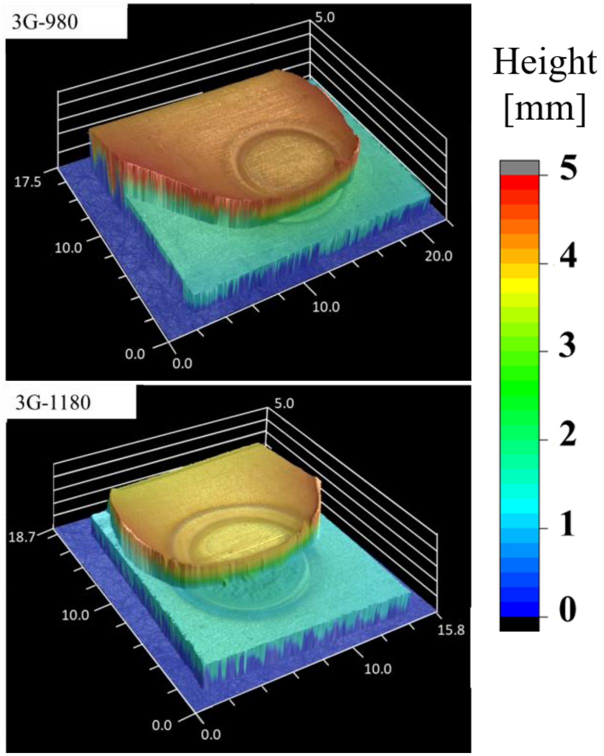


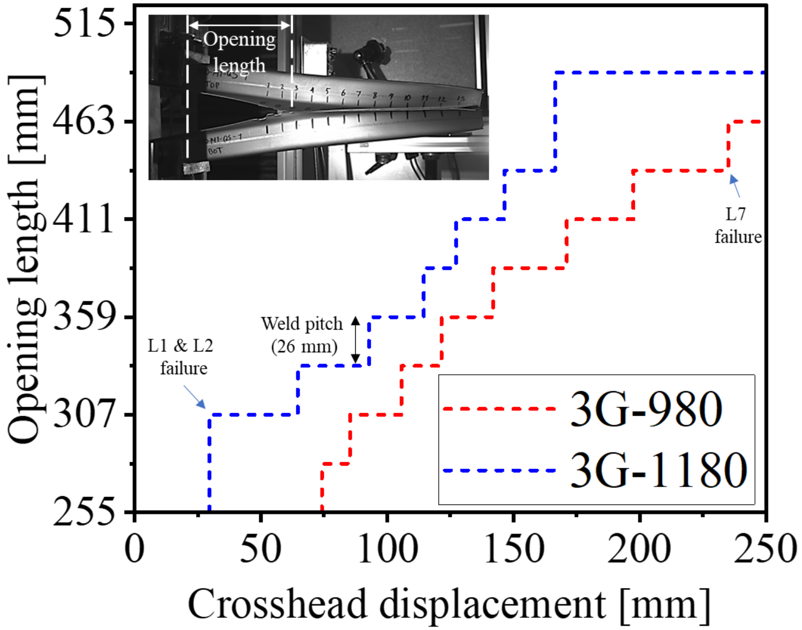
Results indicate an exponentially decreasing (concave) failure loci rather than the convex shape postulated by Seeger

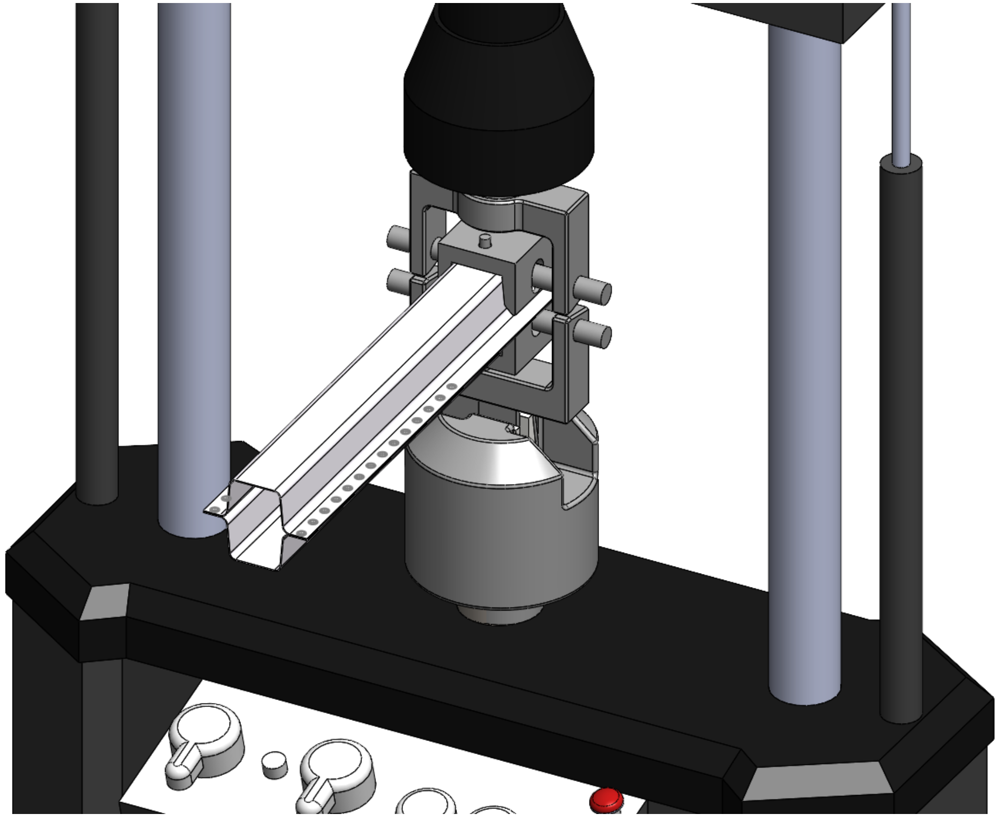
■ Coach peel (short arm)
● Coach peel (medium arm)
▲ Coach peel (long arm)
▲ Tensile strength (KS-II 90°)
▼ Bending strength ($S_B$)

# Task 4

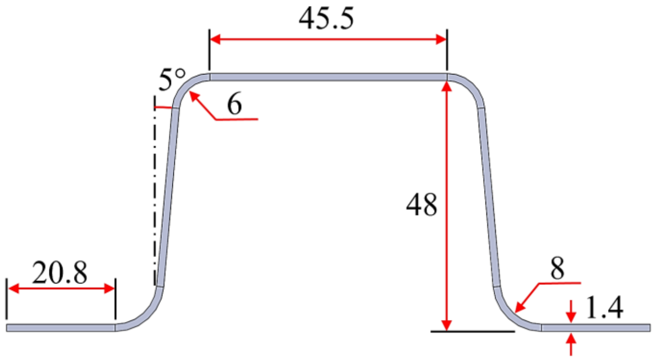
# Mechanical Performance and Failure Behavior of Spot Weld Groups Under Tensile-bending Loading Condition

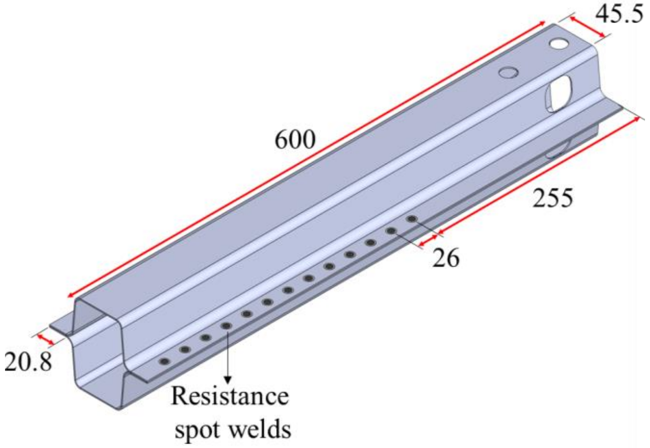


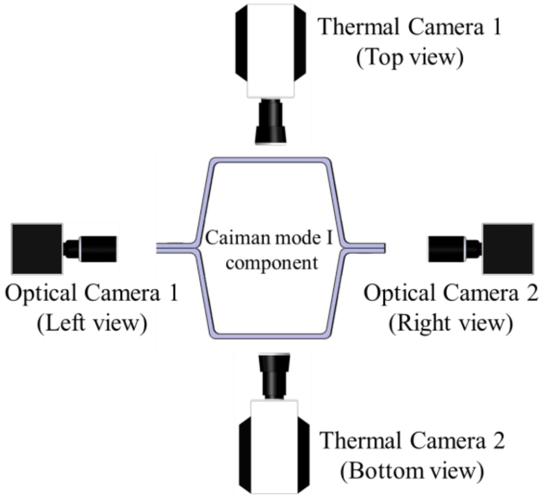


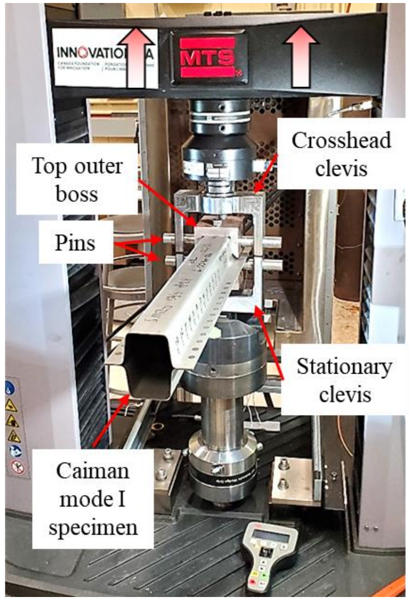


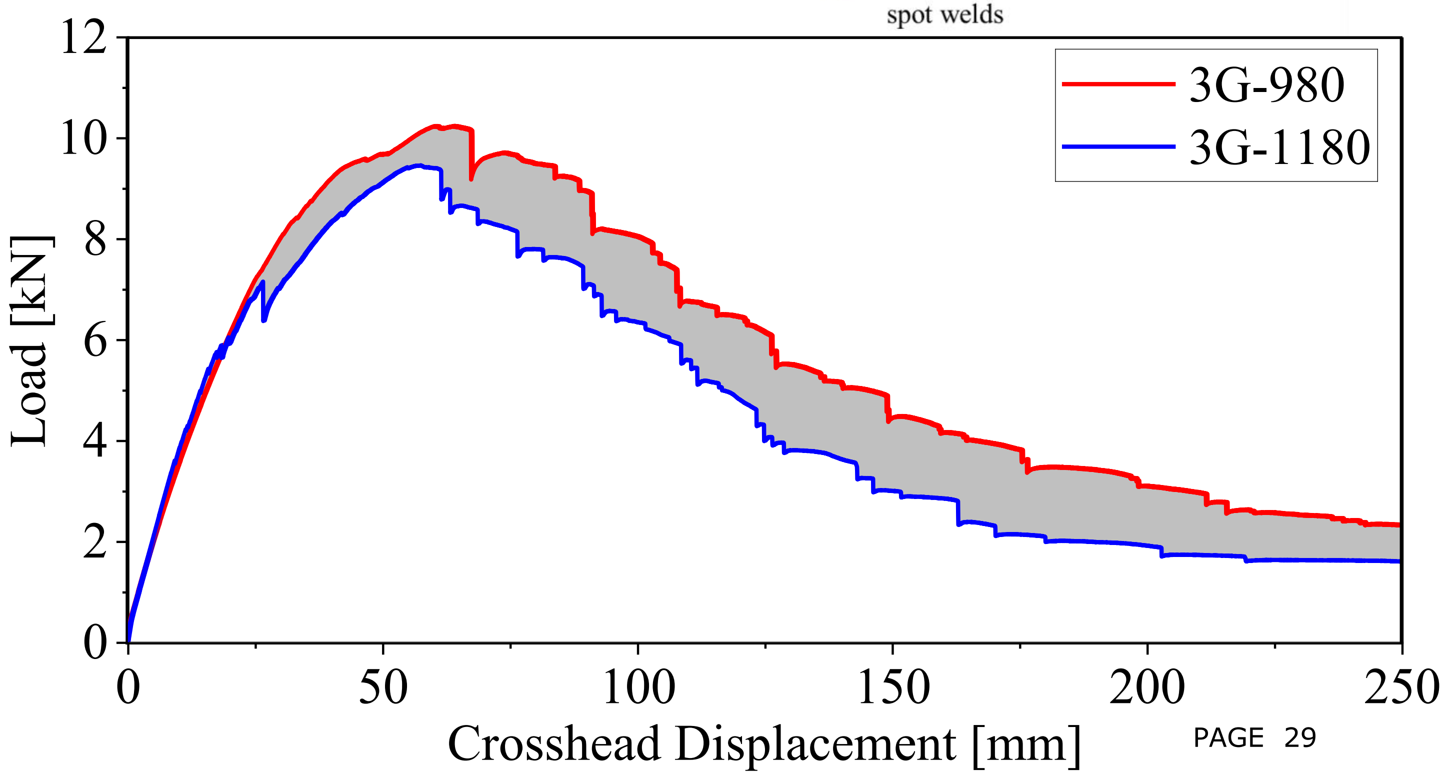
# RSW Weld-group tests methodology: The Caiman test











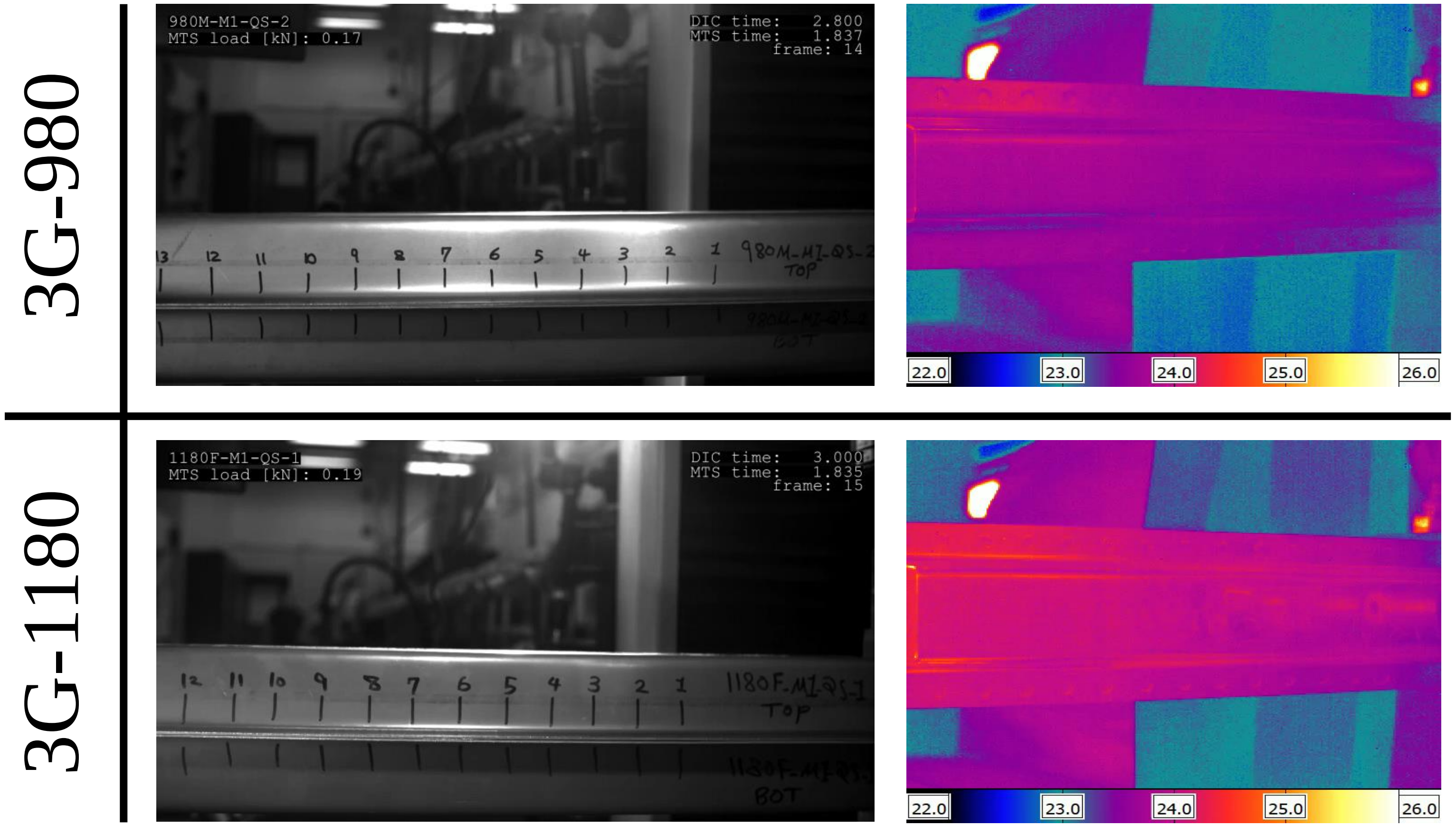
**3G-980 Components exhibited:**

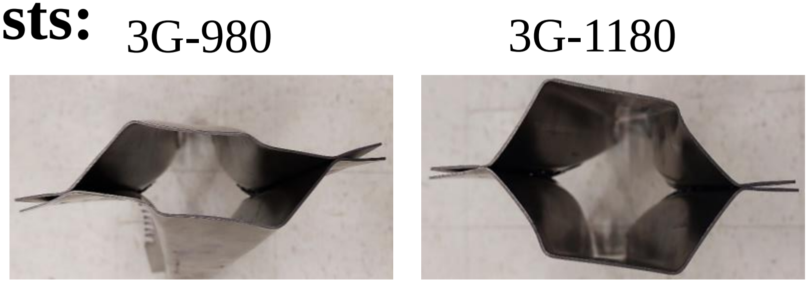
- ➢ 13% higher energy absorption capability

What are the primary factors influencing Energy absorption capability?

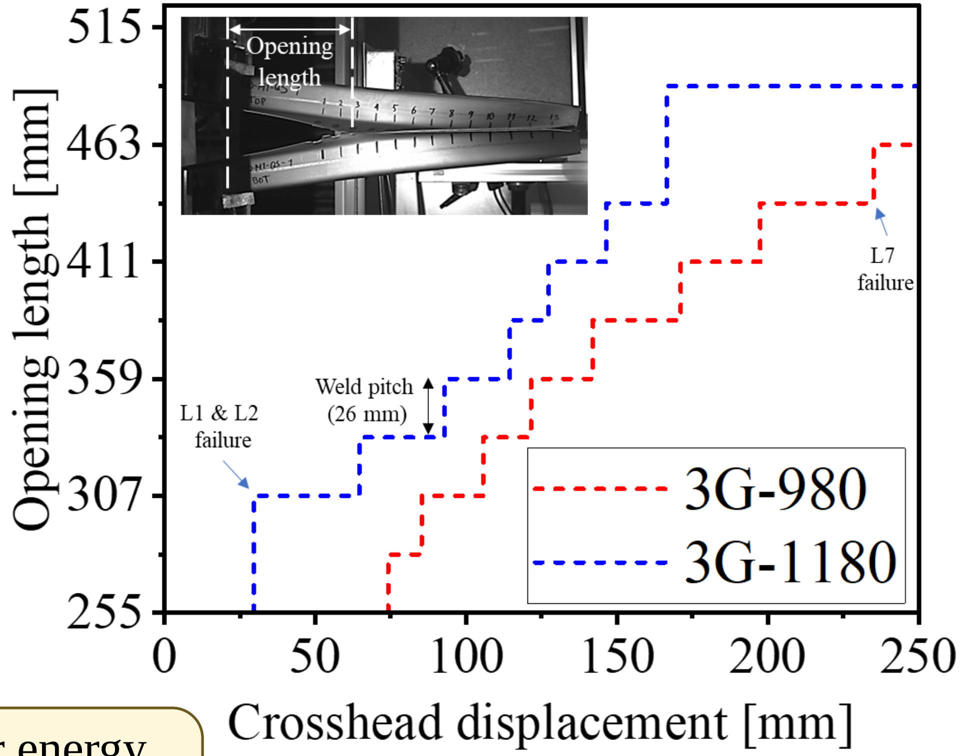
# Comparison of Parent Metal Deformation During Caiman Tests:

Optical sideview footage of Caiman tests: Thermal footage of Caiman tests:



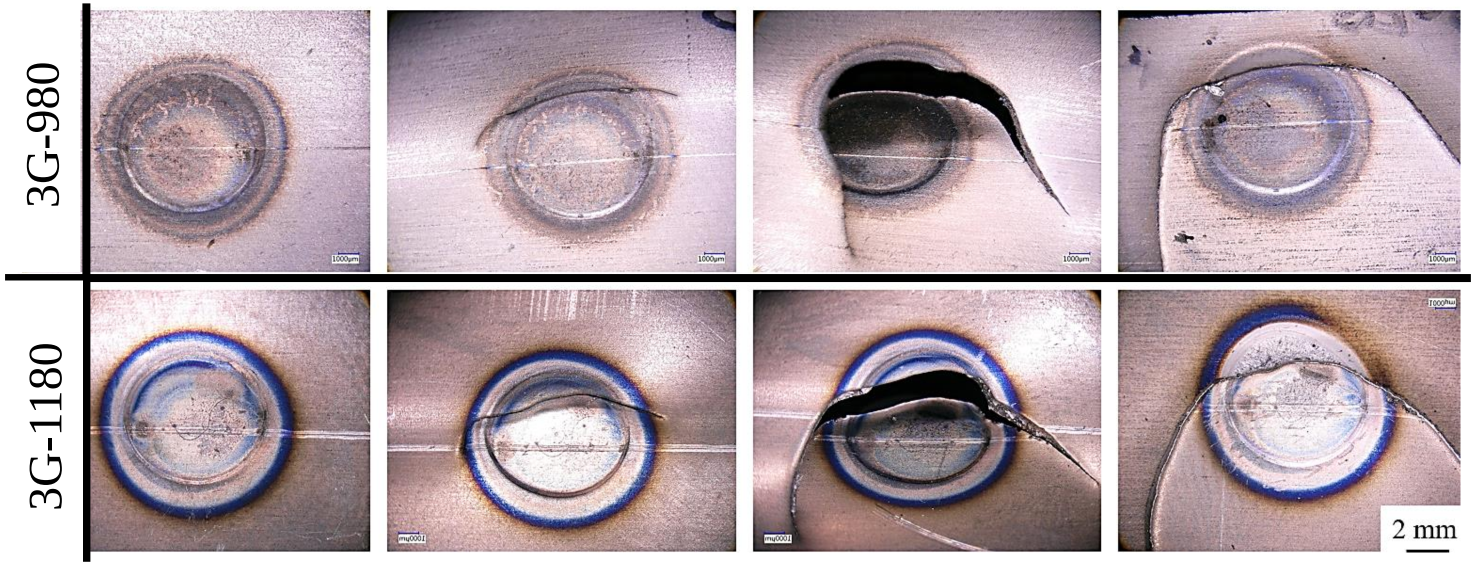


More severe sidewall collapse

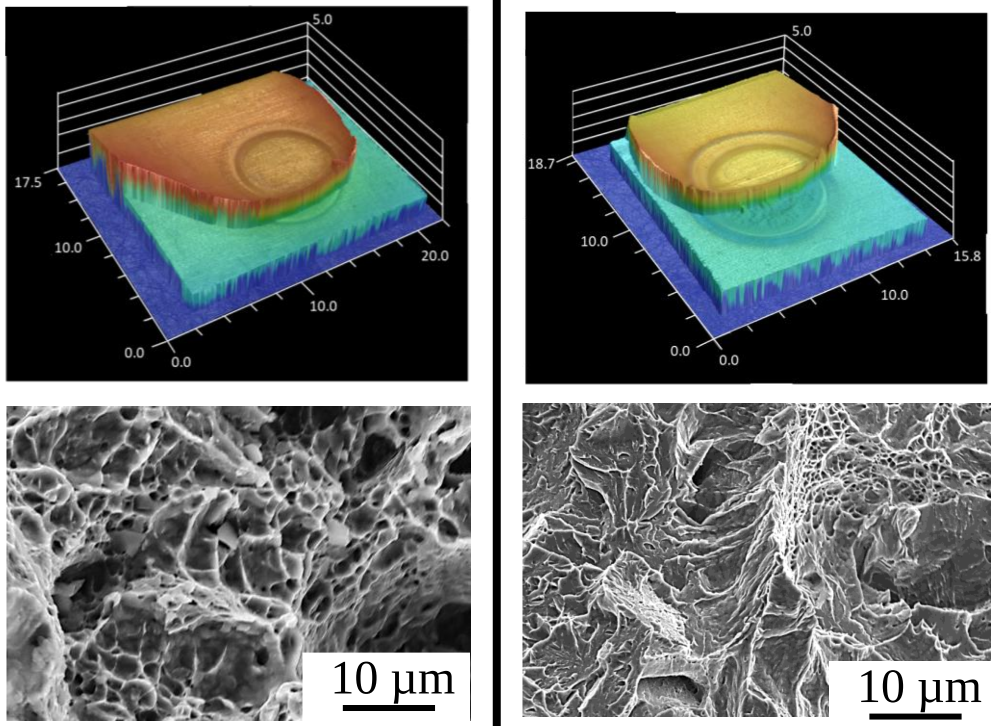


More severe collapse of the 3G-980 channels → Higher plastic work due to parent metal deformation → Superior energy absorption capability

# Comparison of Failure Behaviors During Caiman Tests:



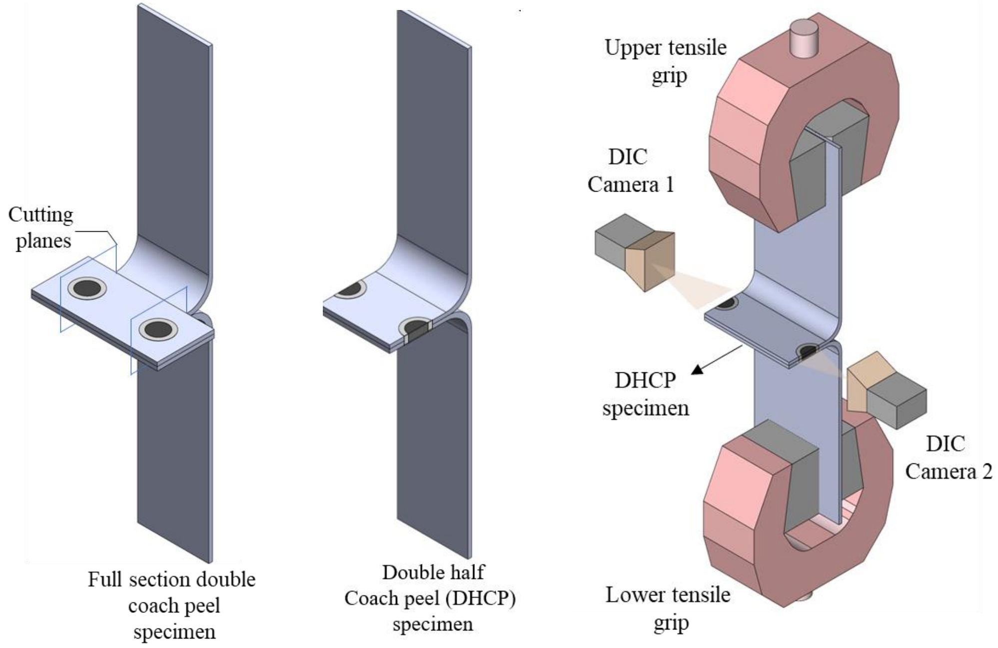
| 3G-980 | 3G-1180 |
|---|---|

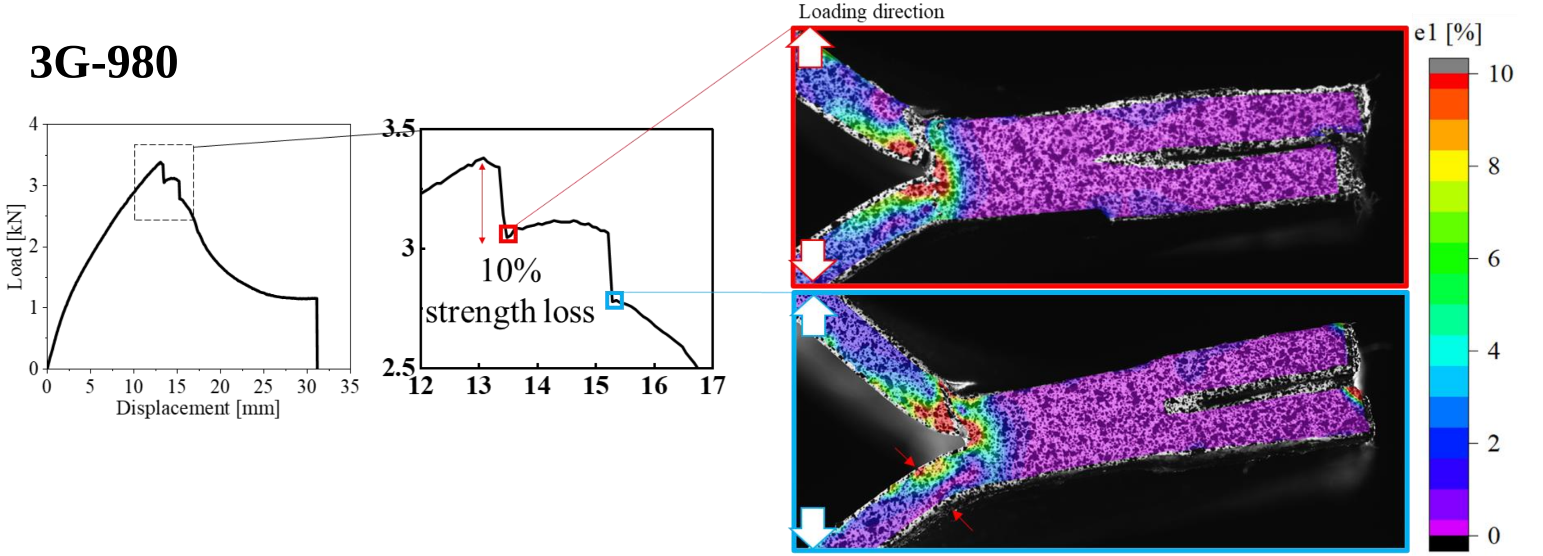


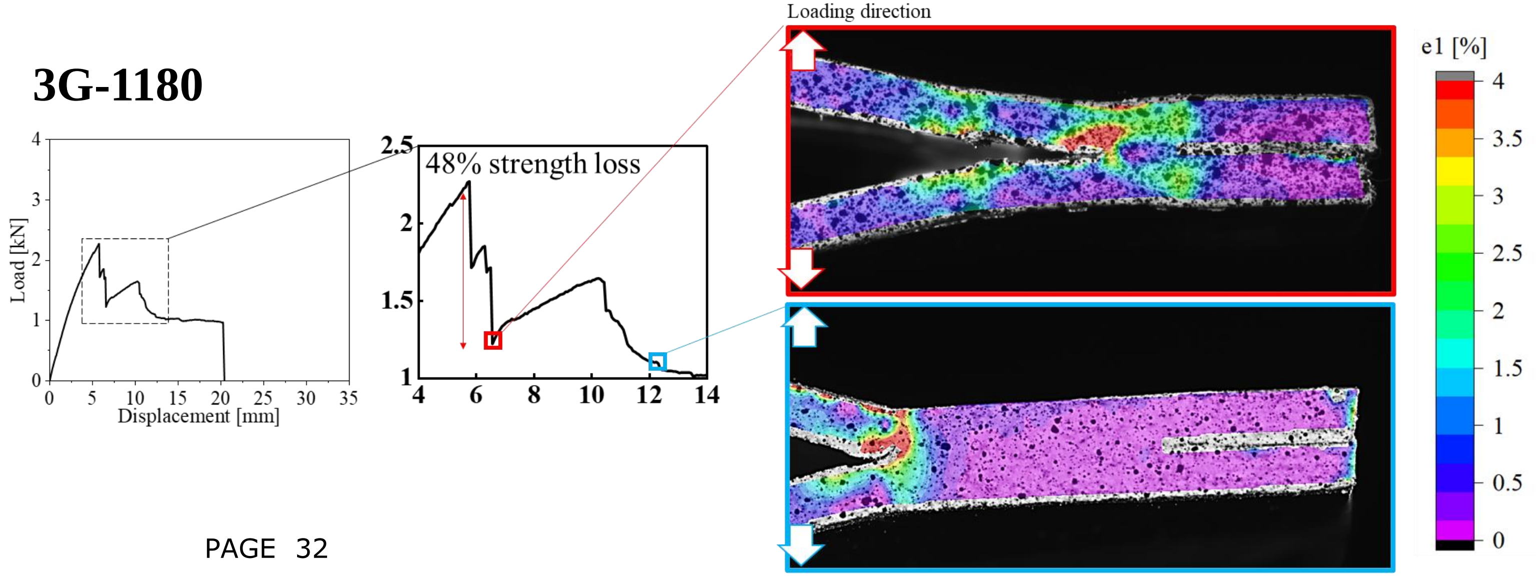
| 3G-980 | 3G-1180 |
|---|---|
| Dimple features | Dimple & Cleavage features |
| Ductile failure | Mixed failure |

# Effect of Failure Mode on Mechanical Performance of RSW Groups

In-situ observation of sequential spot weld failure under tensile bending loads using modified coach peel test:



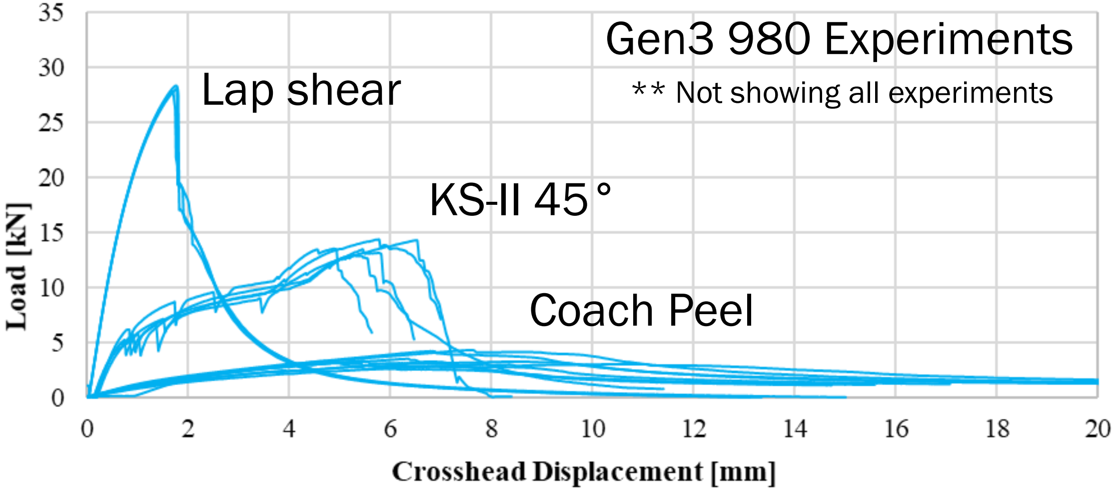




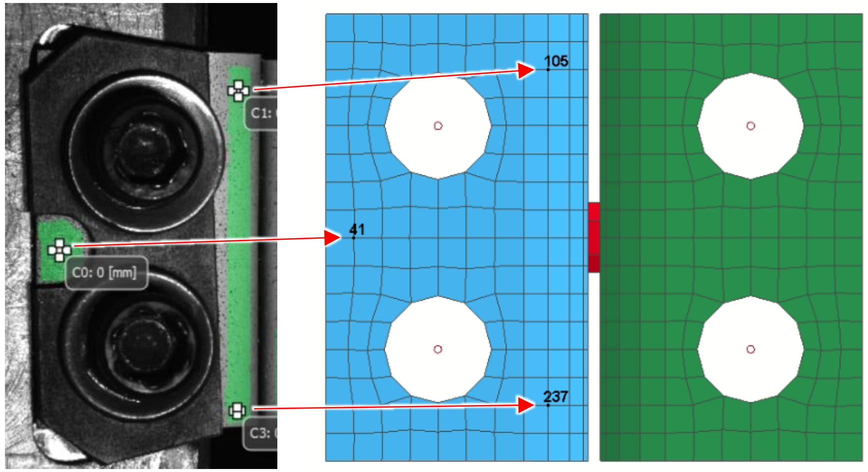
Brittle partial interfacial/ partial pullout failure mode leads to catastrophic loss of strength in sequential failure of spot welds

# Characterization and simulation of single spot weld

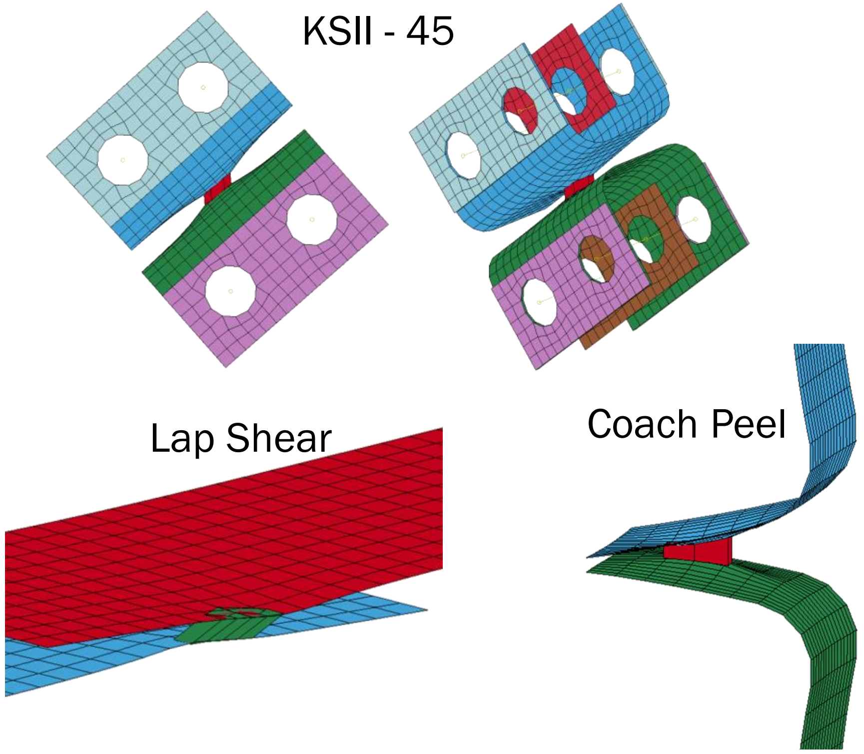
1. Process experimental data force vs displacement – target for simulations



2. Extract simulation boundary conditions from experiments
   - Novel method of KS-II 3D DIC analysis



3. Develop LS-DYNA simulation models of each single spot weld experiment – CAE-level, industry standard



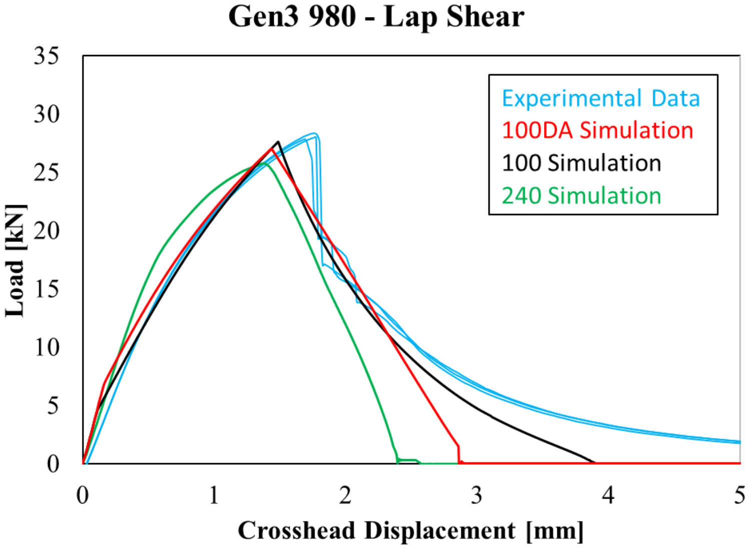
** Not showing all simulation models

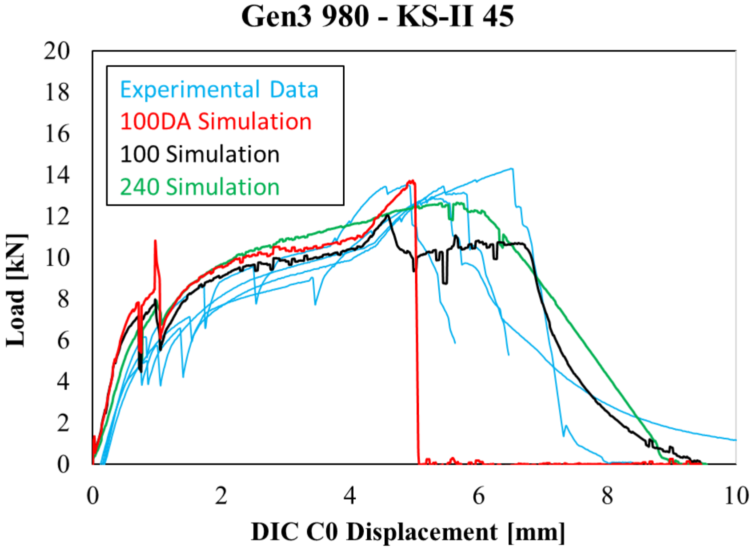
Initial calculation for model bending parameter:

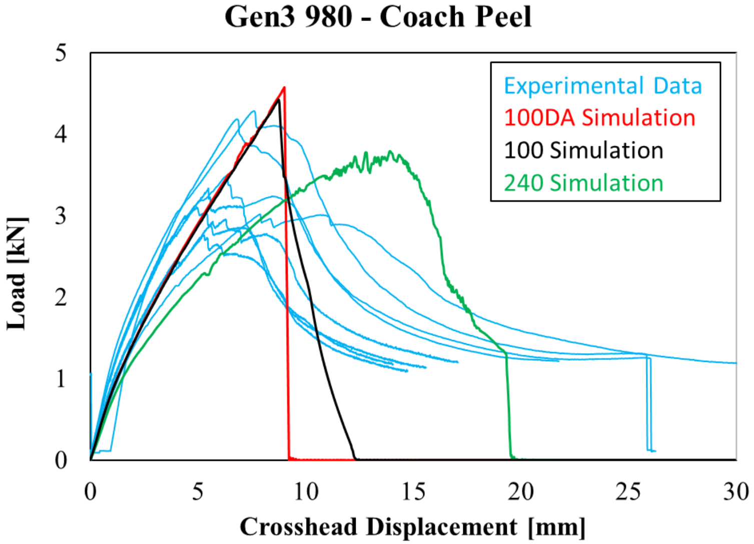
$$Bending\ moment\ (M)[kN.m] = \frac{F_{Max\ CP}[kN] \times L_{CP}[m]}{\sqrt{1-(\frac{F_{Max\ CP}\ [kN]}{F_{Max\ KS-II\ 90^{\circ}}\ [kN]})^2}}$$

# Characterization and simulation of single spot weld

4. Calibrate three different LS-DYNA material models to compare performance


Gen3 980 - Lap Shear


Gen3 980 - KS-II 45


Gen3 980 - Coach Peel

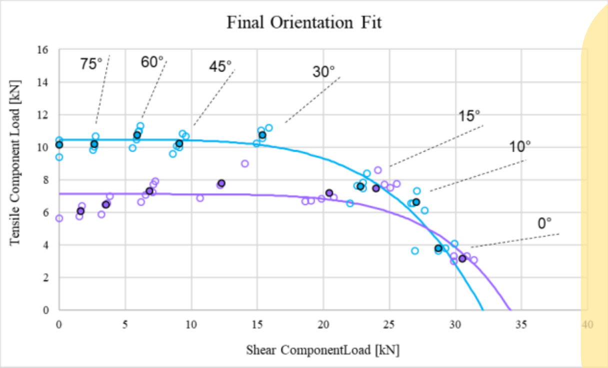
Three joint models examined, good agreement between models and experiments for tensile-shear and mixed loading conditions

**Current model failure criterions have difficulty accurately predicting coach peel**

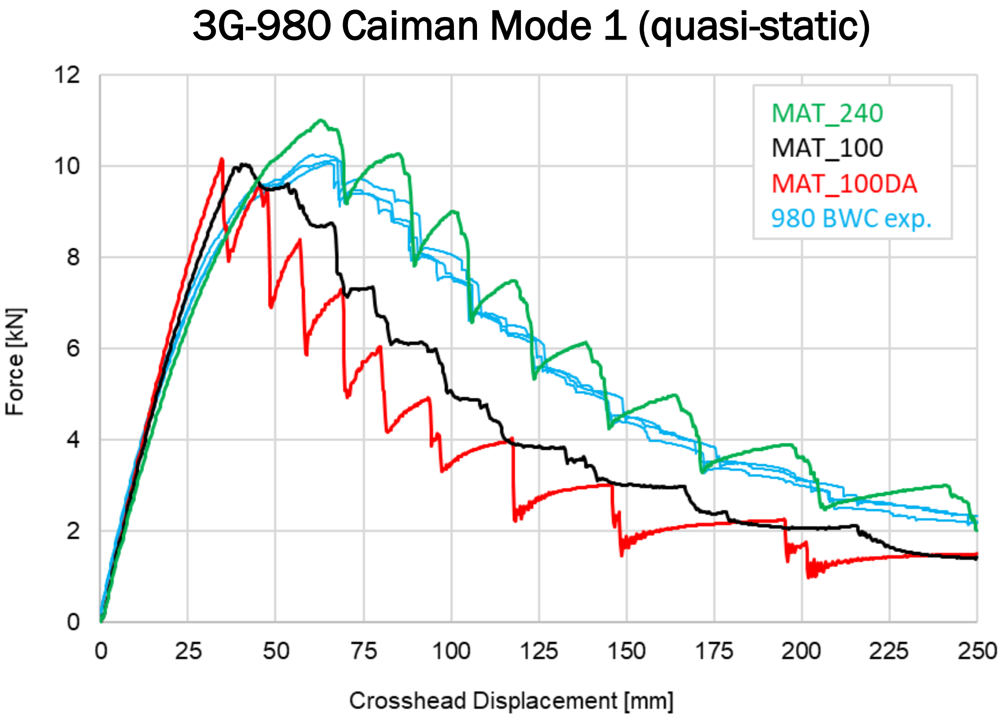
- MAT_100: Has tensile, shear, and bending term in failure model, but limited fracture definitions
- MAT_100DA: Similar to MAT_100, but had to manually over predict bending load to predict component test
- MAD_240: Good fracture behavior but no specific bending term in failure model

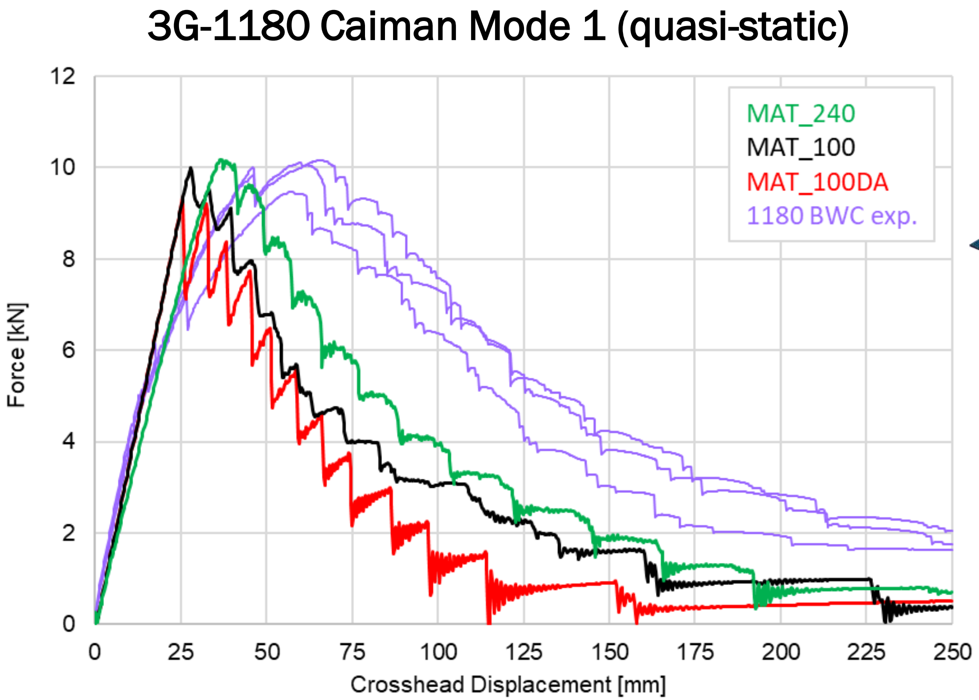
# Characterization and simulation of single spot weld

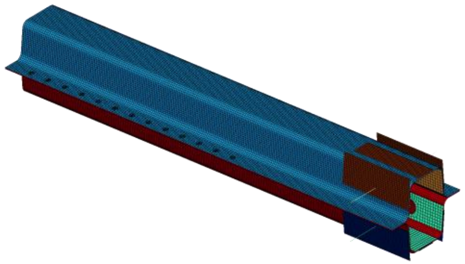
- Spot weld models calibrated from single spot weld experiments
- MAT_240 does best, but all models have difficulty predicting component experiments
- Suspected due to limitations in model failure criterion


Final Orientation Fit

- Calibrated weld failure surface from KS-II single spot weld tests
- Test data has been corrected from ‘ideal’ fixture orientation to final coupon rotation at failure


3G-980 Caiman Mode 1 (quasi-static)


3G-1180 Caiman Mode 1 (quasi-static)



# Conclusions:

This study accounted for the **evolution of load components and moments** until the onset of joint failure during KS-II and CP tests, assessed the **accuracy of conventionally accepted force-based failure criteria**, and clarified the correlation between **mechanical performance and failure behavior of resistance spot weld-groups** under tensile-bending loading conditions.

- Seeger's criteria predicted the failure of 3G-AHSS spot welds in shear-tension loading accurately (average over-prediction of 3.5%)
- Seeger's criteria cannot be extended to bending-dominated loading conditions (average over-prediction of joint bending strength of 66%)
- Novel DIC-based methodologies were proposed that account for:
    - The evolution of geometry during CP tests and the forces/moments applied to the joint
    - The final ratio of shear/tensile forces during KS-II tests applied to the joint

- Two factors dominate the energy absorption capability of 3G-AHSS spot weld-group under tensile-bending loading:
    - Plastic work due to parent metal deformation
    - Joint failure behavior: Failure through the FZ will lead to catastrophic strength loss vs smooth unloading during PO

- The single spot weld mechanical properties were used to build industry-standard LS-DYNA material cards that predict the spot weld failure under combinations of load scenarios.

# Q & A:

## Please use the Q & A feature to ask your questions

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