Failure Characterization of Laser Welds and Spot Welds under Combined Loading Conditions

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Hoon Huh[1)], Jiwoong Ha[2)], Jung-Han Song[3)]

1) Div. of Mechanical Engineering, KAIST, Korea

2) POSCO, R&D Center, Korea

3) KITECH, R&D Center, Korea

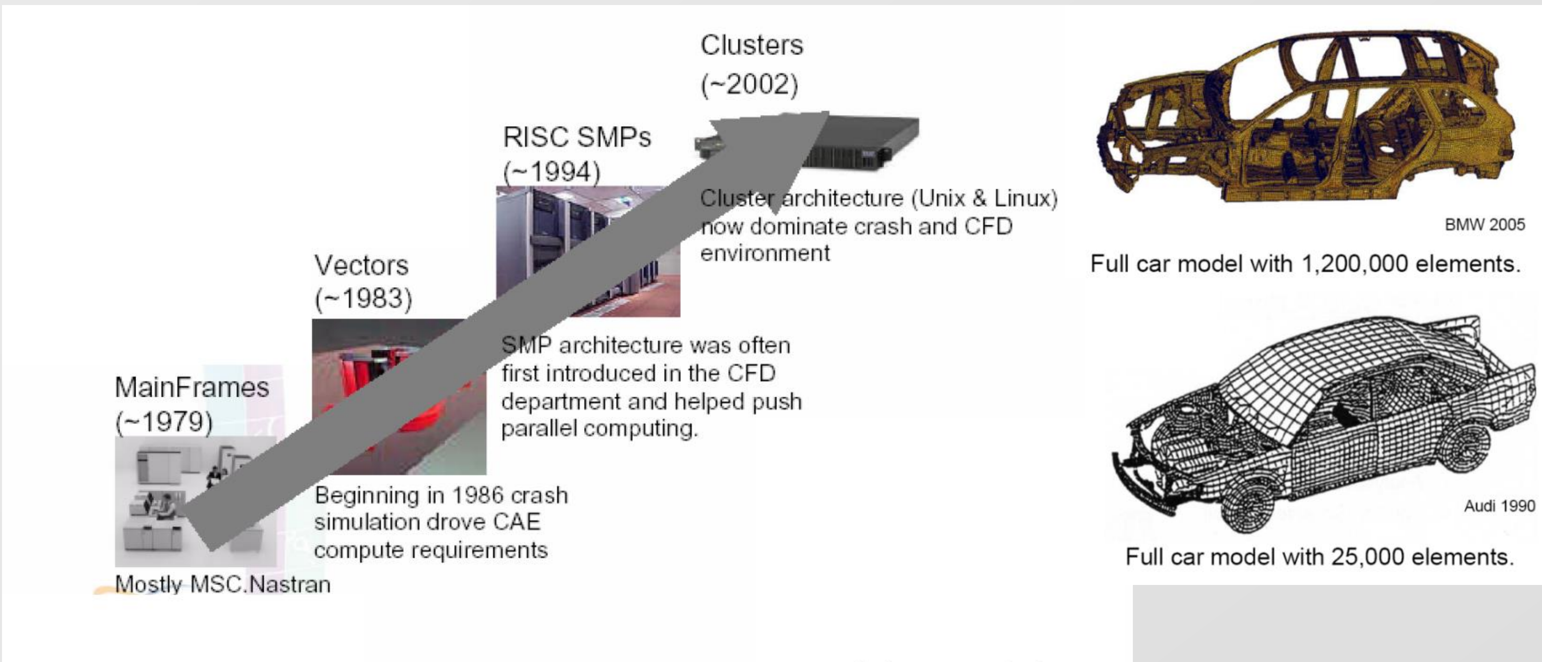
Outline

- Introduction
- Failure Tests and Modeling of the Spot Weld under Combined Loading Condition
- Failure Tests and Modeling of the Laser Weld under Combined Loading Condition
- Conclusion

Introduction

CAE in Automotive Industries

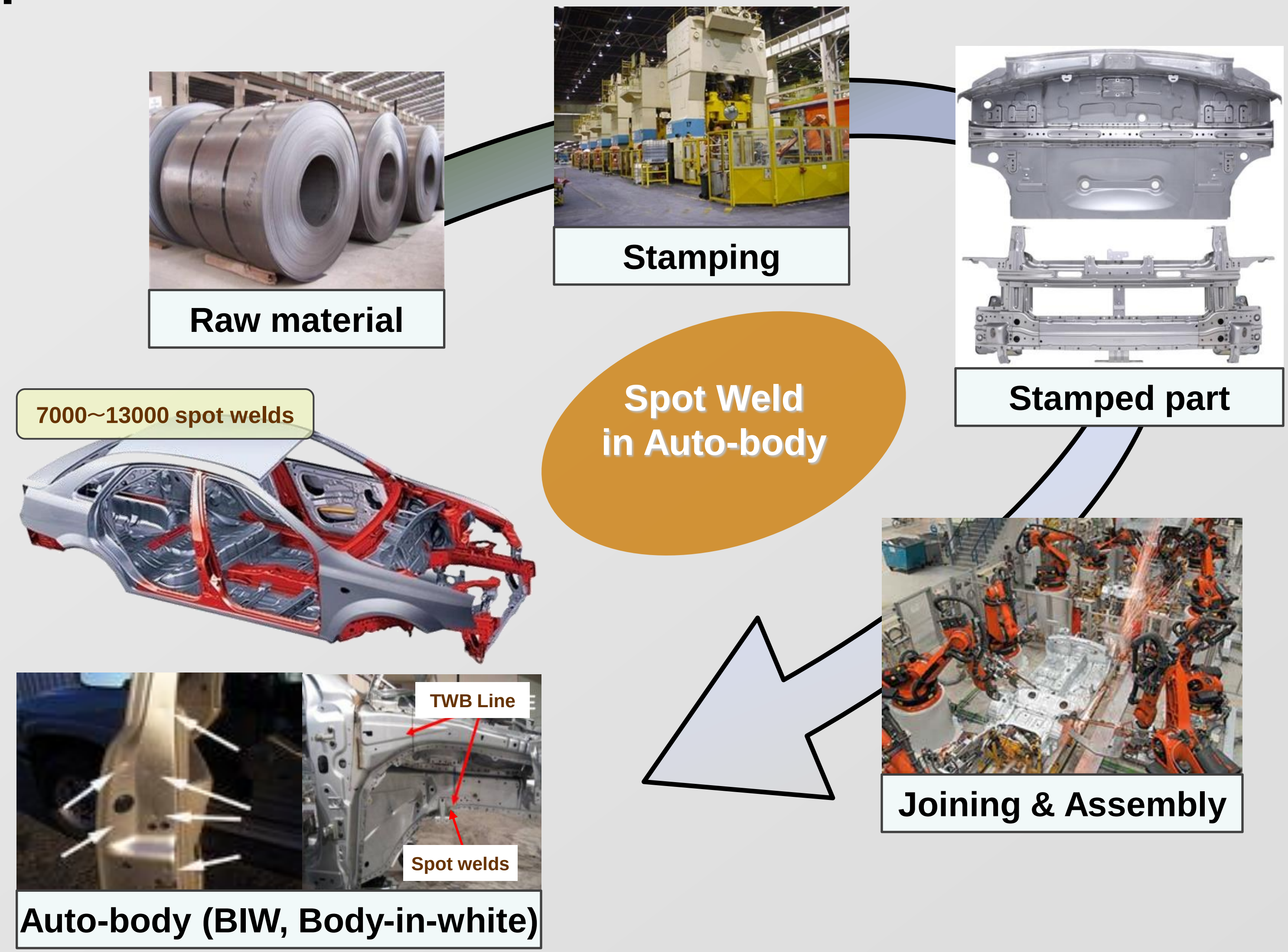
- **Current Requirements using CAE in the Design Stage**



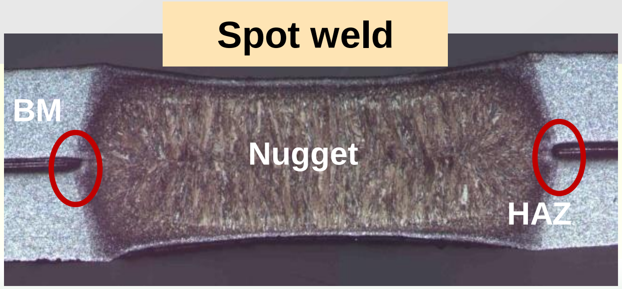
Current requirements for accurate crash analysis in the auto-body design stage

- Failure description of spot welds
- Ductile fracture of panels
- Crash analysis including dummy
- Folding of airbag

Spot welds in BIW



Failure of a spot weld in a car crash



Stress concentration around a spot weld
Weak to the impact load

Impact loading

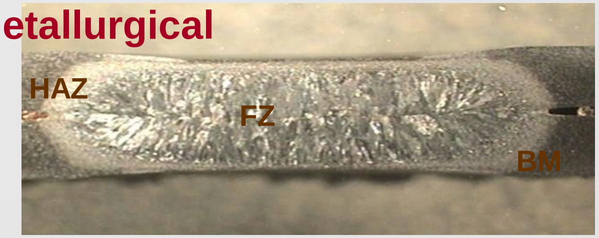
Failure of a spot weld

Affect on Energy absorption, Deformation modes
and Load-bearing capacity of the structure

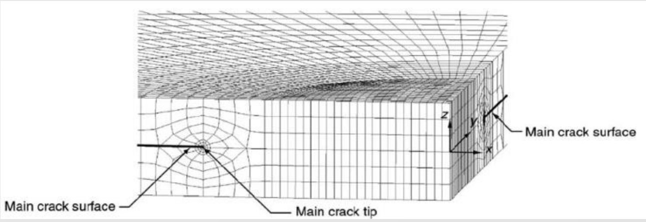
Need to evaluate and predict the failure of a spot weld in the design phase

Modeling Methods of the Spot Weld in FE Analysis

Three heterogeneous metallurgical zones
- Fusion Zone (FZ)
- Heat Affect Zone (HAZ)
- Base Metal (BM)

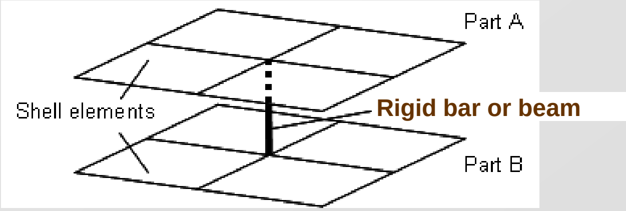


Spot weld



- Use many solid elements
- Provide more accurate stress states
- FE analysis in the level of specimen size for calculating the fracture parameters such as SIF, notch stress and J-integral

Precise model



- Use a single rigid bar or a beam element
- FE analysis for structural member
- In the simplified model, failure is described by using the empirical engineering failure model

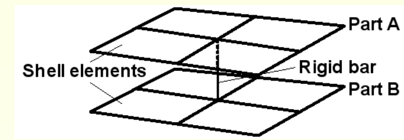
Simplified Model

Crash analysis considering a failure model

Improve the accuracy of a crash analysis

- Compatible FE modeling of welded region
- Secure a reasonable failure model through the failure test
- Approximate the experimental results through a failure model

Existing method considering a failure



Weak point to simulate a failure

- FE modeling
- Lack of experimental data about the failure condition of a spot weld
- Unreliable existing failure model

$$\left(\frac{f_n}{F_N}\right)^2 + \left(\frac{f_s}{F_S}\right)^2 = 1\ ;\ \text{Lee } et\ al.$$

Prediction of the failure of a spot weld in the design phase → Design change → Improvement of crashworthiness → Safety Design

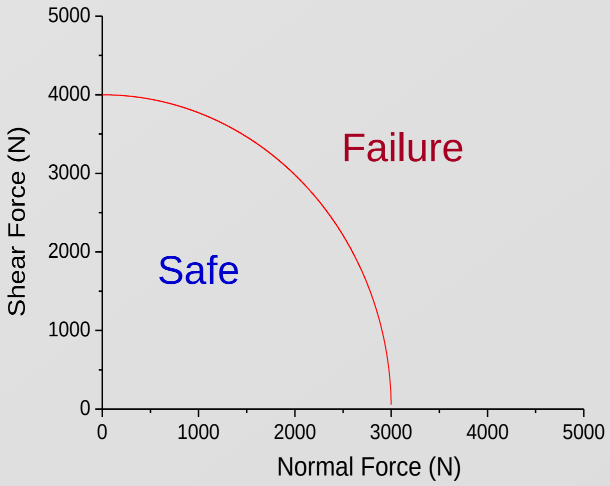
Empirical Engineering Failure Model of the Spot Weld

- **Engineering failure model of spot weld**
  - **Description of the failure line based on the force acting on the spot weld**
  - **The spot weld fails if the forces are outside of the failure line**
  - **The commercial software such as LS-DYNA 3D and ABAQUS/Explicit employs an basic engineering failure model such as;**

$$\left(\frac{f_n}{F_N}\right)^2 + \left(\frac{f_s}{F_S}\right)^2 = 1$$

where, f_i : Cross-sectional force on the spot weld

F_I : Failure load of the spot weld



Conventional failure model of a spot weld

- **Failure model of a spot weld**
  - **Prediction of a failure of a spot weld for the structure analysis**
  - **Function of the axial force and the shear force acting on a spot weld**
  - **When a force acting on a spot weld is out of a failure contour, the finite element model of a spot weld is deleted**
  - **Not consider the dynamic effect on the failure charateristics**

Lee *et al.* (1998)

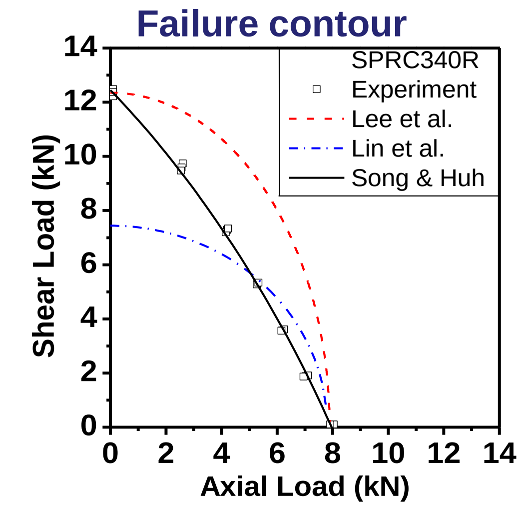
$$\left(\frac{f_n}{F_N}\right)^2 + \left(\frac{f_s}{F_S}\right)^2 = 1$$

- Elliptic shape failure curve
- The most commonly used in a commercial code

Lin *et al.* (2003)

$$\left[1-2\alpha+2\alpha^2\right]\left(\frac{f_n}{\pi D t \tau_0}\right)^2 + \left[\frac{1}{3}+\left(\frac{4t}{\pi D}\right)\right]\left(k\frac{f_s}{\pi D t \tau_0}\right)^2 = 1$$

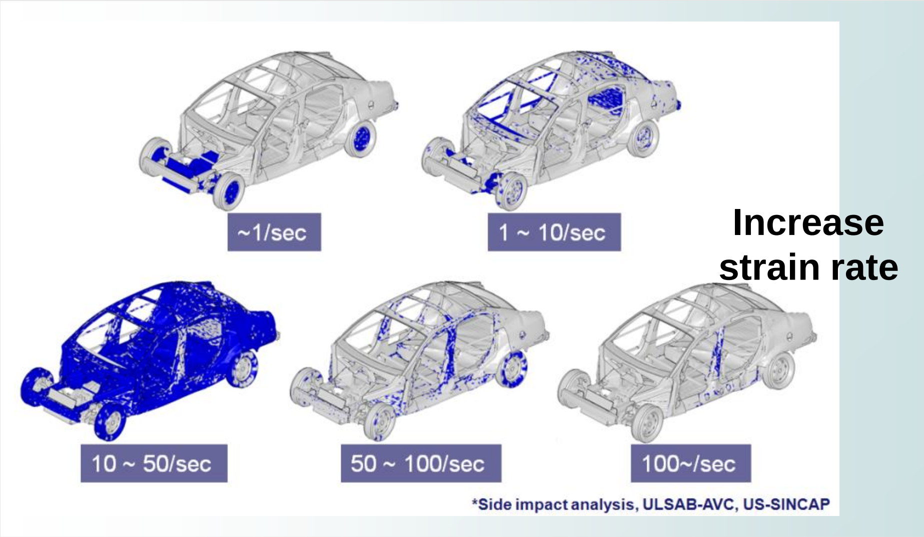
- Approximation of the failure of a spot weld through the axial failure force acting on a spot weld
- Decrease of the failure load with increasing the loading angle



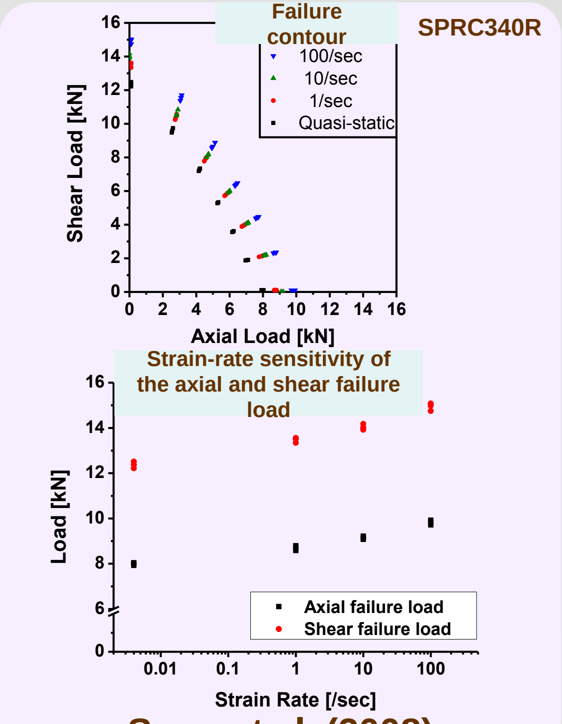
* B. Langrand & C. Combescure (2004)

Failure tests of welds w.r.t. strain rate

- Failure tests of spot and laser welds w.r.t. strain rate
  - In case of spot welds, failure load increases and failure contour is extended with an increase of strain rate
  - Need for study on the failure tests of laser welds w.r.t. strain rate



Increase strain rate

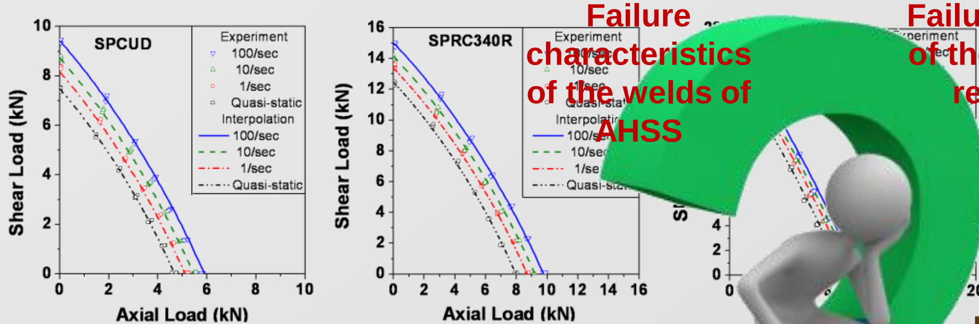


Song et al. (2008)

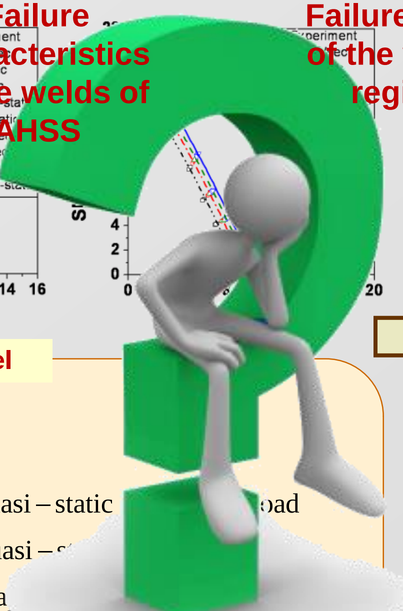
The effect of strain rate on the failure characteristics of laser welds?

Motivation and Scope

- **Need for a failure model of welded region of AHSS to improve the accuracy of a crash analysis**
  - **Accelerate the application AHSS to reduce the weight of BIW**
  - **Secure the reliability of a car crash analysis in the design phase**
  - **Need to consider the dynamic failure of the spot weld of AHSS**



Failure characteristics of the welds of AHSS



Failure model of the welded region?

Dynamic failure model

$$\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2 + \beta\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)\left(\frac{f_s}{F_S(\dot{\varepsilon})}\right) + \left(\frac{f_s}{F_S(\dot{\varepsilon})}\right)^2 = 1$$

$$F_N(\dot{\varepsilon}) = F_{N_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^p\right)$$

$$F_S(\dot{\varepsilon}) = F_{S_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^p\right)$$

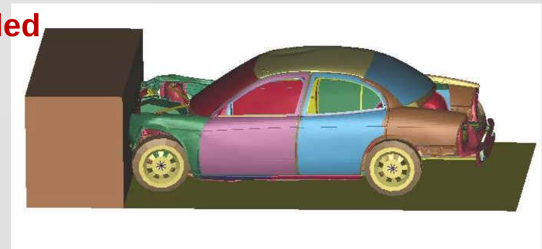
F_{N_0} : Quasi – static … load

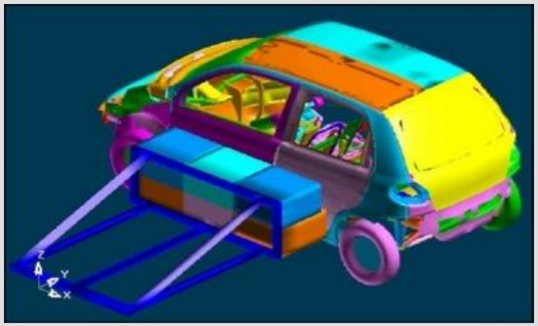
F_{S_0} : Quasi – …

β : Sha…

C, p : Strain – … parameter

$\dot{\varepsilon}_0$: Reference strain rate (quasi-static)





Improve the accuracy of a car crash

Research Scope

- **Objective**
  - Investigate the failure load of the welded region to provide the engineering failure model, which facilitates the failure description of the welded region in the FE analysis of the structural members such as crash analysis of an auto-body
- **Contents**
  - Design the fixture and the specimen for failure tests of the spot and laser weld under combined loading condition
  - Failure tests of welded specimens under combined axial and shear loading condition
  - Construct the failure model of the welded region in a macroscopic manner for the FE analysis

Failure Tests and Modeling of the Spot Weld under Combined Loading Condition

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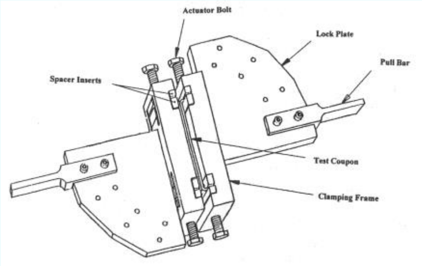
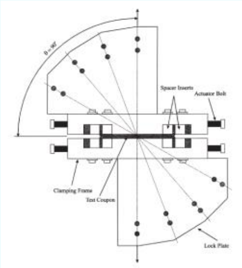
Fixture and Specimen Design for Failure Tests

- **Failure Test of the Spot Weld under Combined Load**
  - **Impose the combine axial and shear load on the spot weld using specially designed fixture**

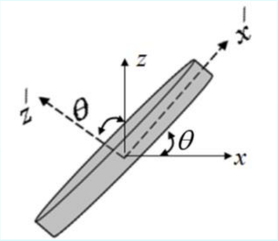


Y. L. Lee et al. (1998)

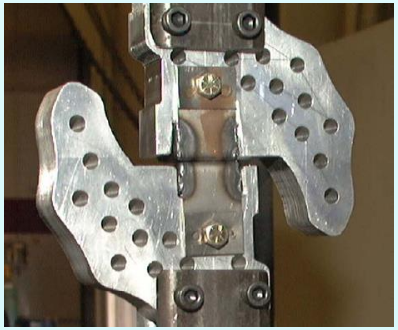


H. Kang et al. (2000)

Calculation of failure load



B. Langrand and C. Combescure (2004)



C. Madasamy et al. (2004)

Axial load: $F_N = F_z \cos\theta$

Shear load: $F_S = F_z \sin\theta$

$$\frac{F_S}{F_N} = \frac{F_z \sin\theta}{F_z \cos\theta} = \tan\theta$$

where θ is initial inclined angle

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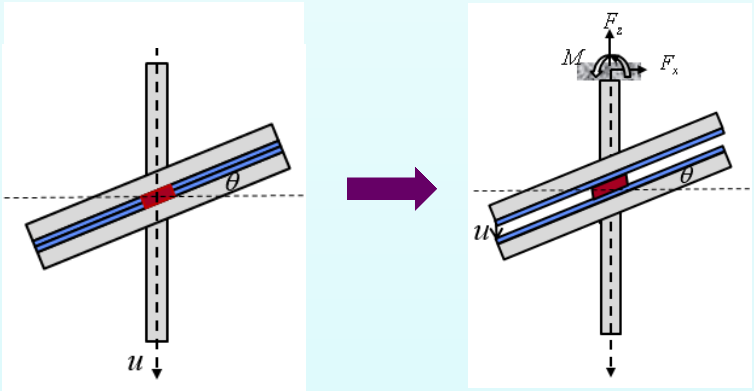
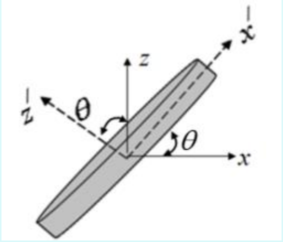
Fixture and Specimen Design for Failure Tests

- **Schematic Evaluation of the Established Testing Fixture**
  - **Assumption**
    - ✓ **Fixture show rigid body translation in the direction of z with the amount of u_z**



$$M = F_z \cos\theta\, u_z \sin\theta = \frac{F_z \sin 2\theta}{2} u_z$$

Resultant force on the spot weld



Global Coordinate $F_x,\ F_z,\ M_y = \dfrac{F_z \sin 2\theta}{2} u_z$

Local Coordinate $F_N = F_z \cos\theta - F_x \sin\theta$

$$F_S = F_z \sin\theta + F_x \cos\theta$$

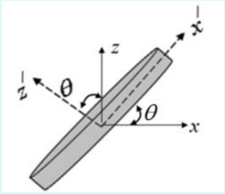
$$\frac{F_S}{F_N} = \frac{F_z \sin\theta + F_x \cos\theta}{F_z \cos\theta - F_x \sin\theta} = \tan(\theta + \beta) \quad where\ \beta = \frac{F_x}{F_z}$$

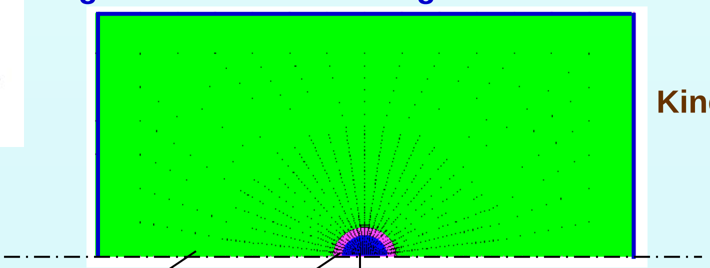
$$\frac{F_S}{F_N} = \frac{F \sin\theta}{F \cos\theta} = \tan\theta$$

is not valid

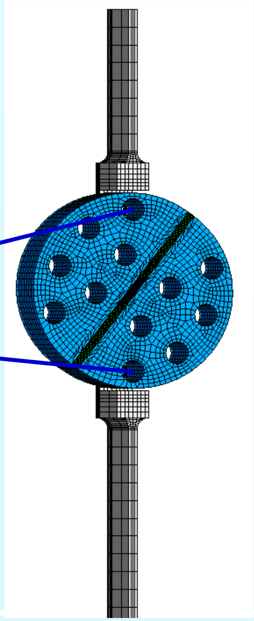
Fixture and Specimen Design for Failure Tests

- FE Evaluation of the Established Testing Fixture
  - Use ABAQUS/Standard
  - Symmetric condition: ½ model
    - ✓ Inclined angle: 15˚, 30˚, 45˚, 60˚ 75˚
    - ✓ Connection of lock plate and pull bar
      - – Use kinematic constraints to impose clamping condition
    - ✓ Specimen
      - – Base Metal: SPRC340R 1.2t



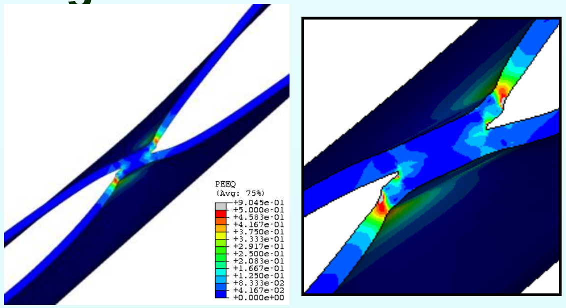


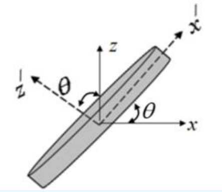
Kinematic constraint



Fixture and Specimen Design for Failure Tests

- **Analysis results (Clamped Condition)**
  - **The ratio of shear load to normal load is different from the tangent of initial inclined angle of spot weld**

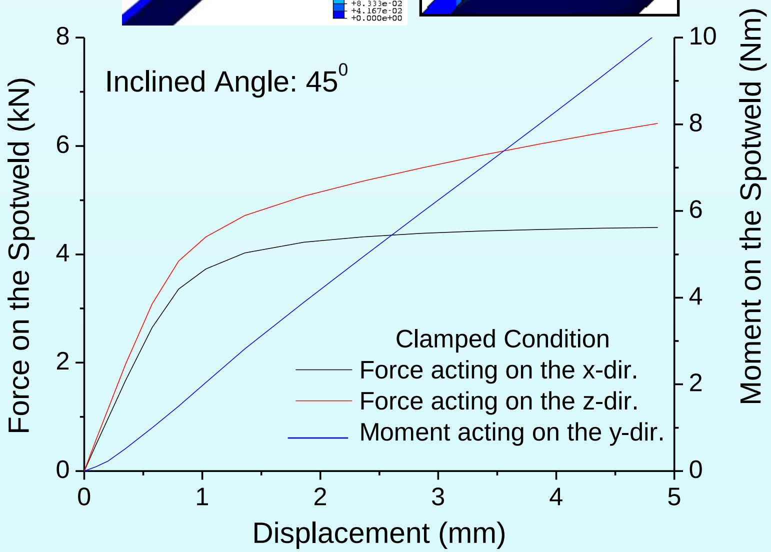


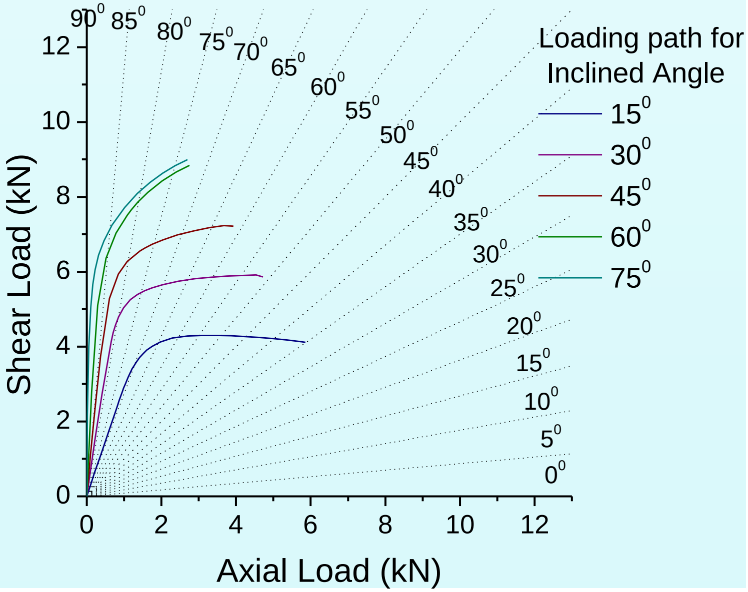


$$F_N = F_z \cos\theta - F_x \sin\theta$$

$$F_S = F_z \sin\theta + F_x \cos\theta$$

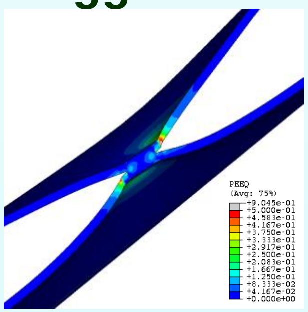
$$\frac{F_S}{F_N} = \frac{F_z \sin\theta + F_x \cos\theta}{F_z \cos\theta - F_x \sin\theta} = \tan(\theta + \beta) \quad where\ \beta = \frac{F_x}{F_z}$$

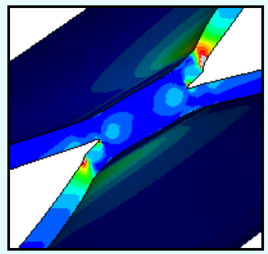




Fixture and Specimen Design for Failure Tests

- **Analysis results (Pin-Joint Condition)**
  - **Pull bar and lock plate is connected with pin-joint constraints**
  - **Nugget is rotated due to the bending deformation**

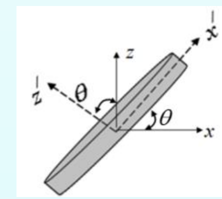


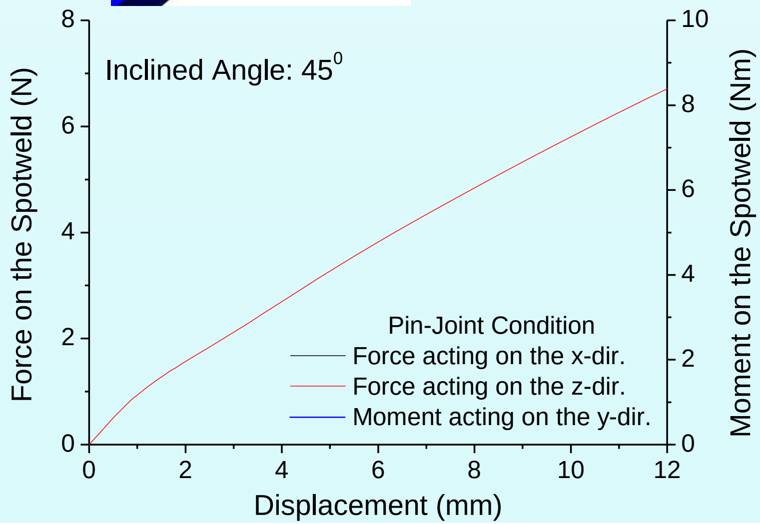


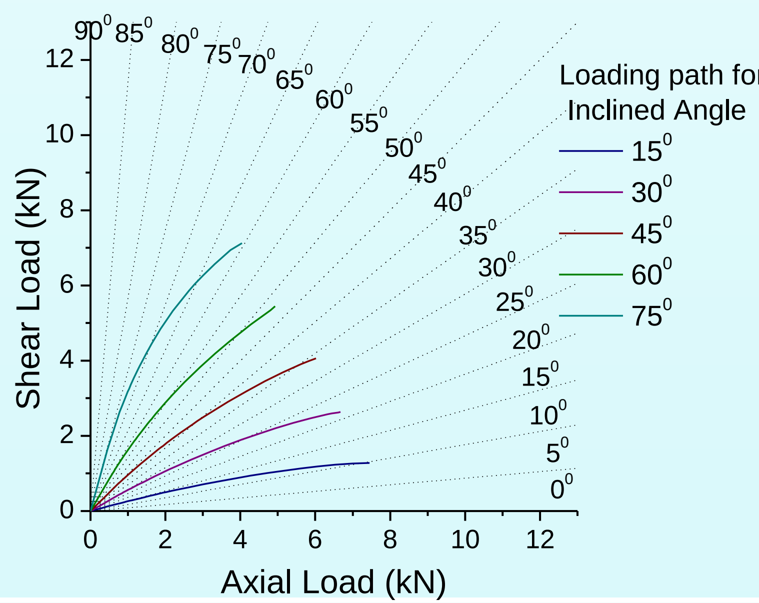
$$F_N = F_z \cos\theta$$

$$F_S = F_z \sin\theta$$

$$\frac{F_S}{F_N} = \frac{F_z \sin\theta}{F_z \cos\theta} = \tan\theta$$

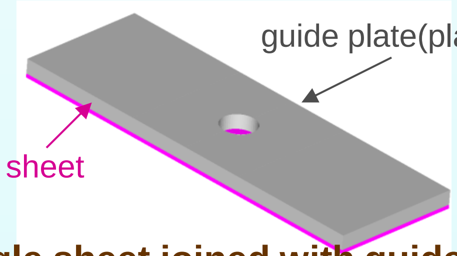




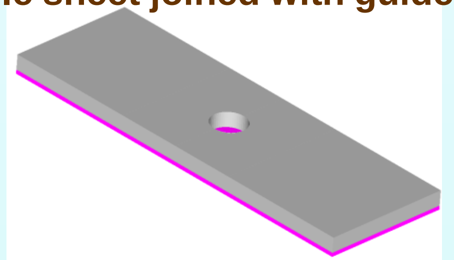


Fixture and Specimen Design for Failure Tests

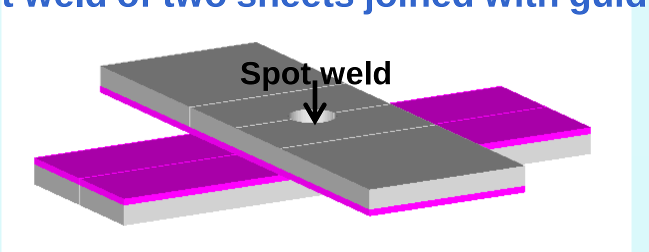
- **Install the Guide Plates into Specimen**
  - **To Reduce the bending deformation**



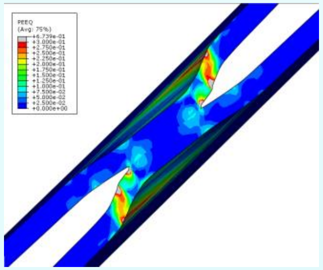
Single sheet joined with guide plate

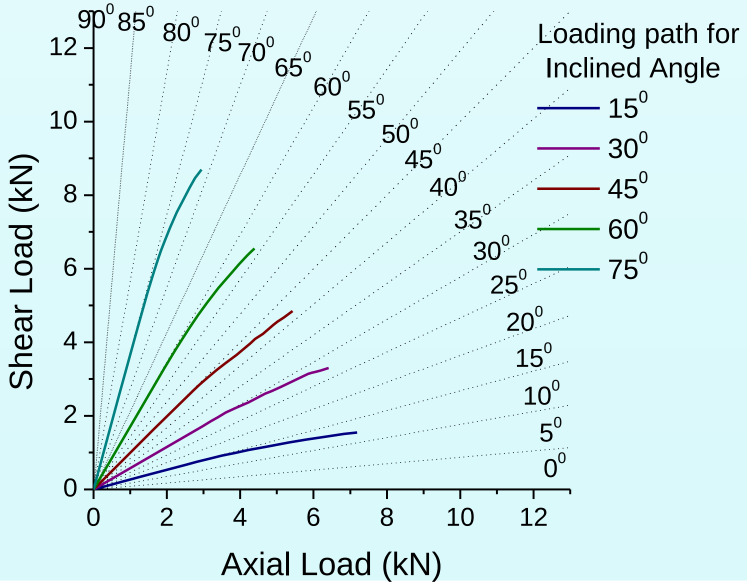


Spot weld of two sheets joined with guide plate



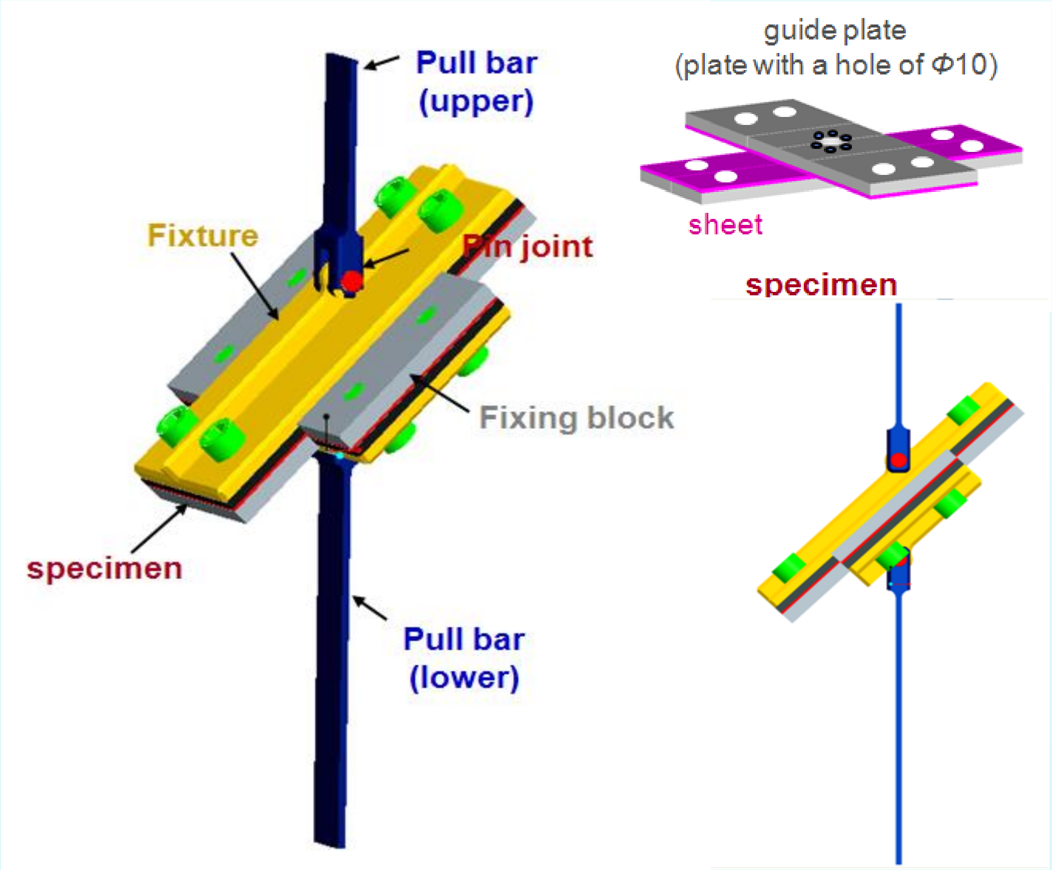
Modified Specimen





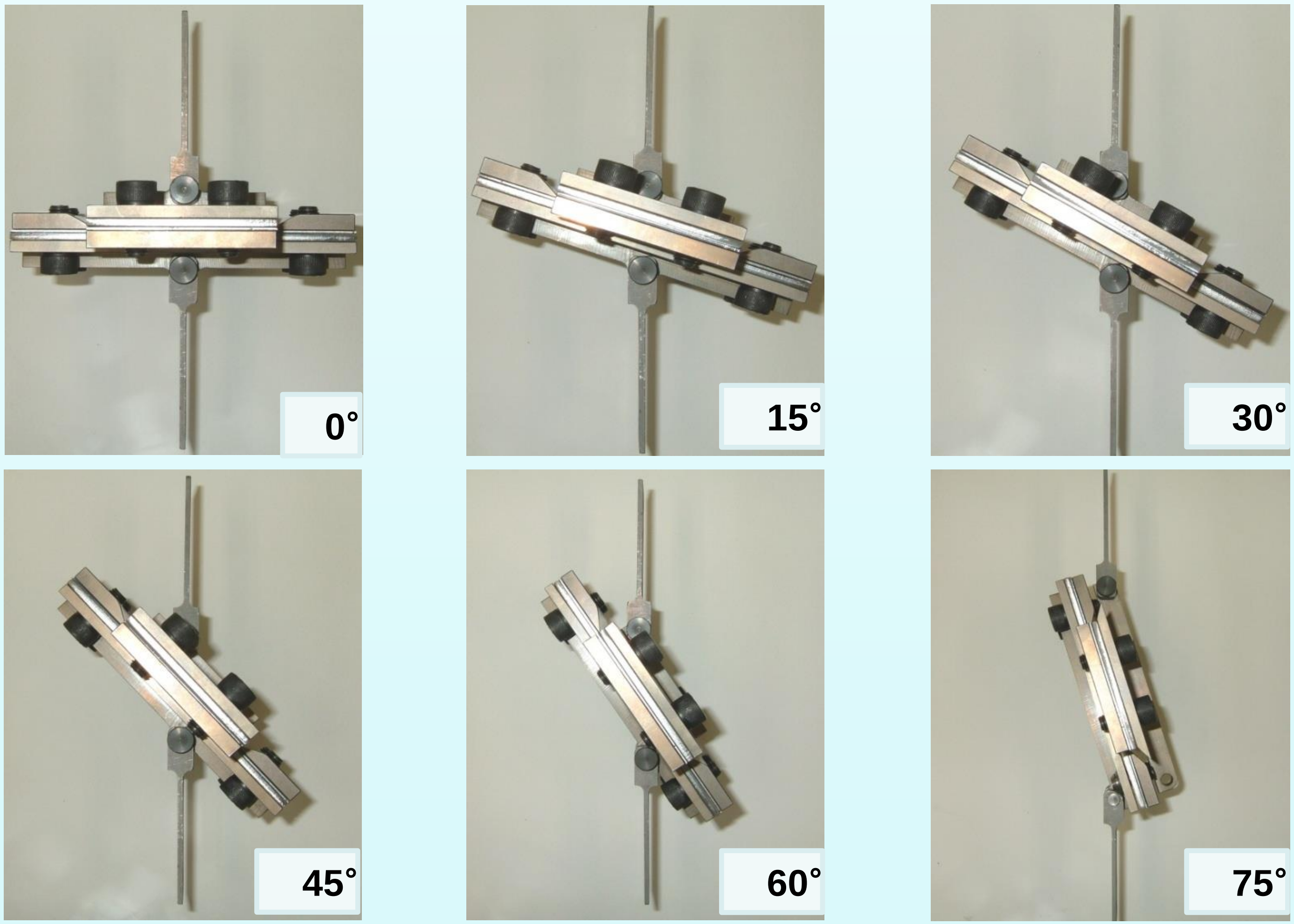
Fixture and Specimen Design for Failure Tests

- **Schematic diagram of Fixture and Specimen**
  - **Failure test of the spot weld under combined loading condition**



Fixture and Specimen Design for Failure Tests

- **Fixture Sets for Failure Tests of the Spot Weld**



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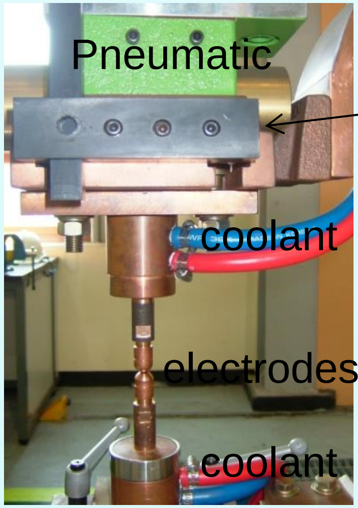
Failure Tests of the Spot Weld under Combined Load

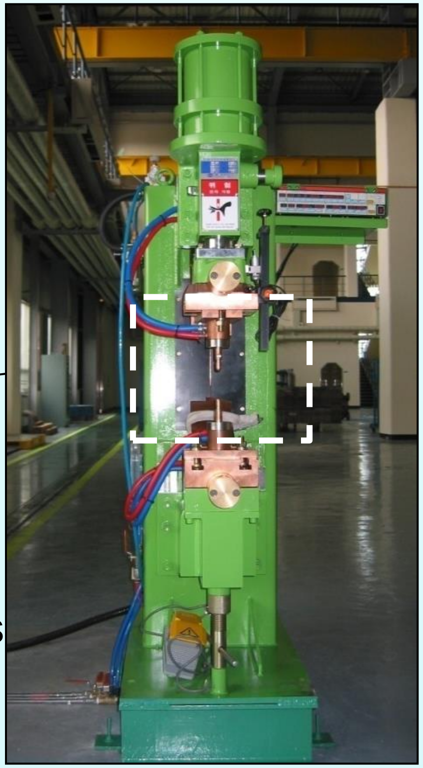
- **Experimental Condition**
  - **Base material: SPRC340R 1.2t**
    - ✓ INSTRON 4206
    - ✓ Crosshead speed: 2 mm/min
    - ✓ Inclined angle: 0˚, 15˚, 30˚, 45˚, 60˚, 75˚
      - Modified cross-tension
    - ✓ Inclined angle: 90 ˚
      - Pure shear test

0° 15° 30° 45° 60° 75° 90°

Failure Tests of the Spot Weld under Combined Load

- **Spot Welding Condition**
  - **Base material: SPRC340R 1.2t**
  - **Use static spot/projection welding machine(POSCO)**
    - ✓ **Welding Condition**
      - – Welding current: 7.6 kA
      - – Welding force: 3.0 kN
    - ✓ **Time Schedule**
      - – Squeeze time: 18cycle
      - – Welding time: 15cycle
      - – Holding time: 20 cycle

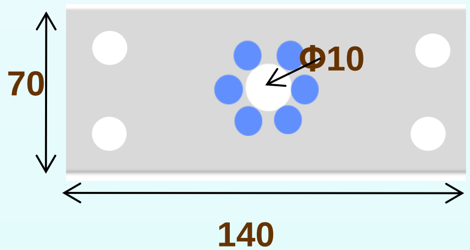


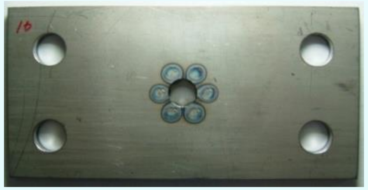


Failure Tests of the Spot Weld under Combined Load

- **Specimens (SPRC340R 1.2t)**

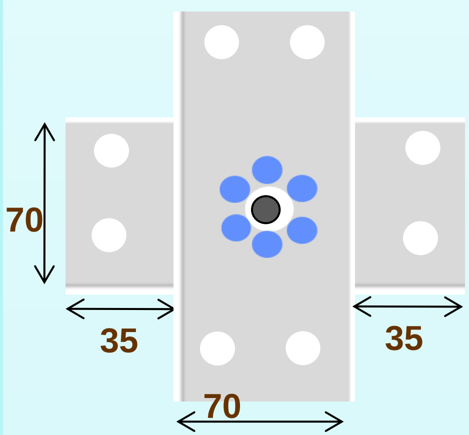
Spot welding of guide plate and base material



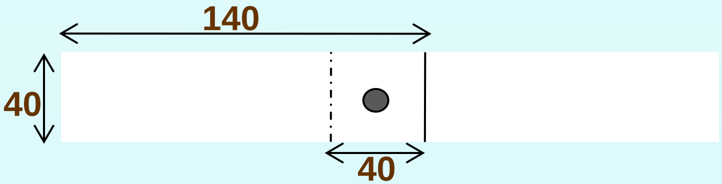


Spot welding of two sheets joined with guide plate

Spot welding of three sheets for pure shear test



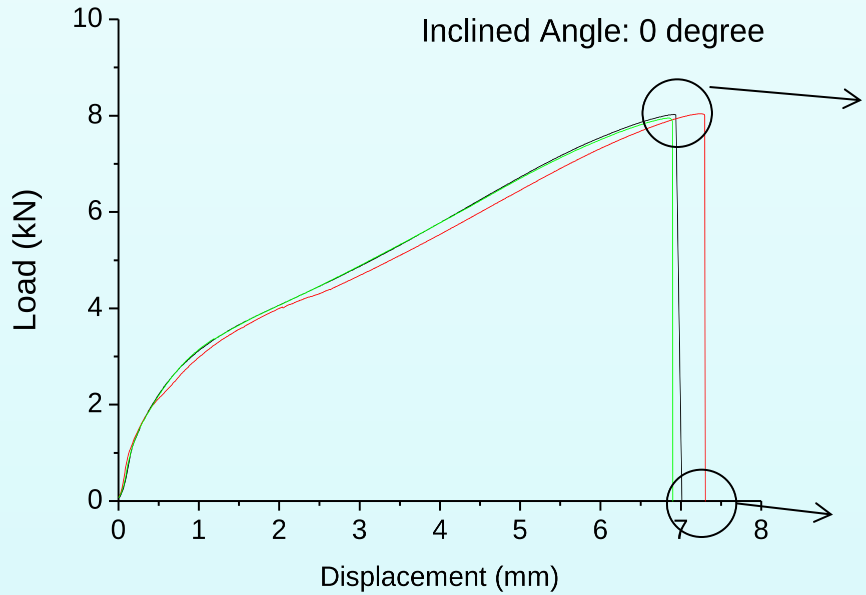
Specimen for modified CT tests

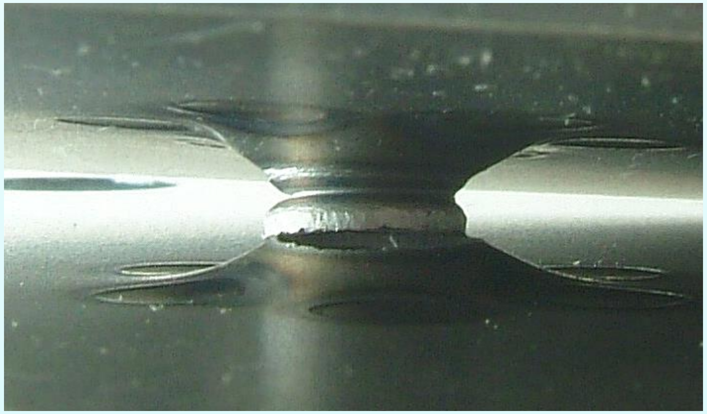


Specimen for pure shear test

Failure Tests of the Spot Weld under Combined Load

- **Experimental Result**
  - **Inclined angle: 0˚**
    - ✓ **Load–Displacement curves**

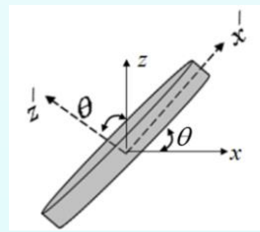


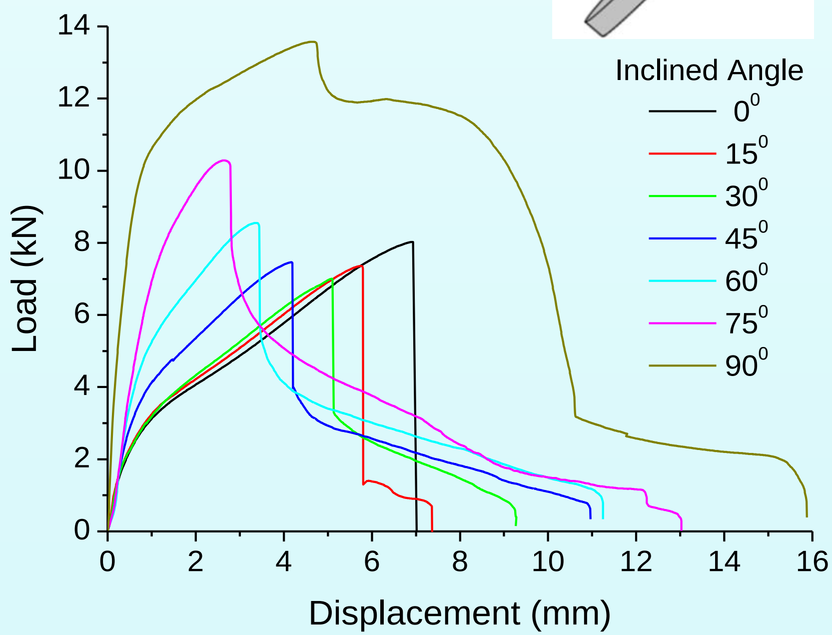


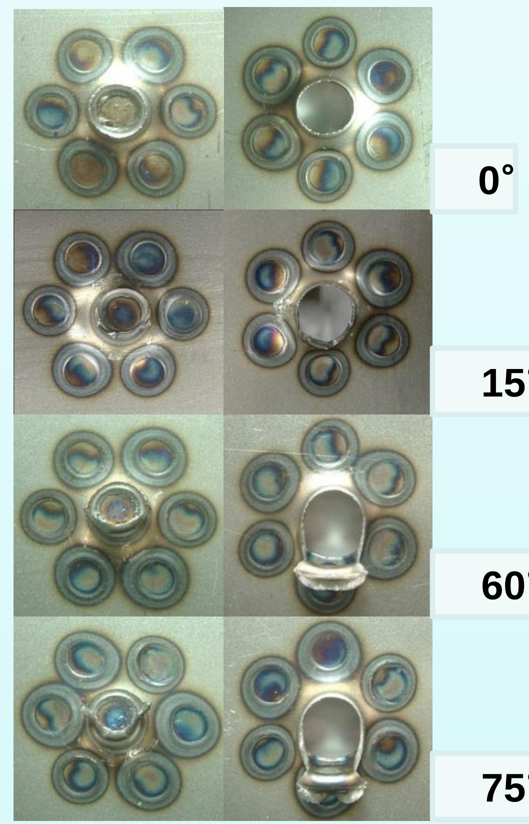
Specimen	1	2	3
Max. Load (kN)	8.025	8.037	7.968

Failure Tests of the Spot Weld under Combined Load

- **Experimental Result with Various Loading Angles**
  - **Load characteristics and fracture surfaces of the spot weld**



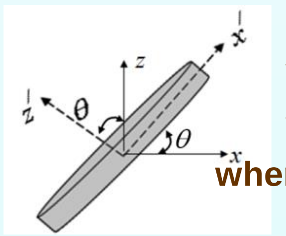




Failure Tests of the Spot Weld under Combined Load

Failure Load and Failure Curve of the Spot Weld

- **Material:SPRC340R 1.2t**



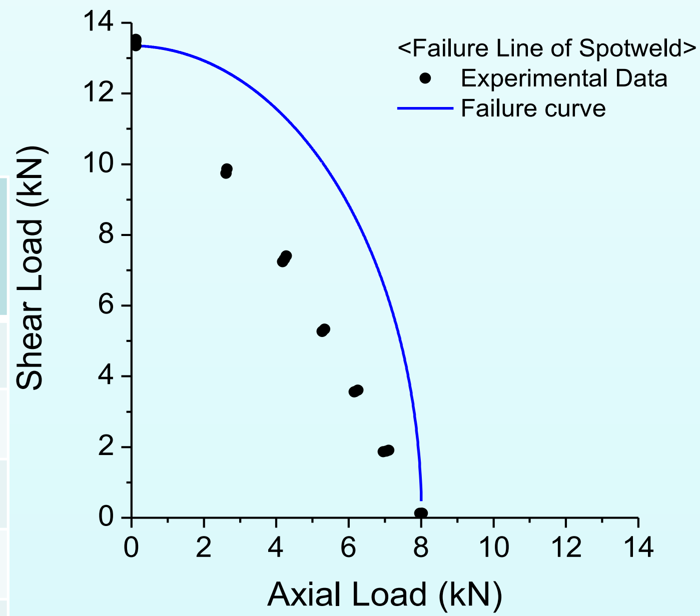
Axial load: $F_N = F\cos\theta$

Shear load: $F_S = F\sin\theta$

where θ is initial inclined angle

Run no.	Inclined angle (°)	Failure load (kN)
01,02,03	0	8.025, 8.037, 7.968
04,05,06	15	7.286, 7.361, 7.204
07,08,09	30	7.134, 7.219, 7.113
10,11,12	45	7.462, 7.453, 7.542
13,14,15	60	8.448, 8.364, 8.553
16,17,18	75	10.21, 10.09, 10.41
19,20,21	90	13.35, 13.48, 13.57

$$\left(\frac{f_N}{7.97}\right)^2 + \left(\frac{f_S}{13.35}\right)^2 = 1$$



Conventional failure model can not describe the failure load

→ New failure model

Dynamic failure tests of spot welds of AHSS

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2
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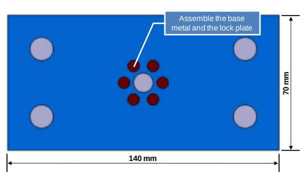
Failure test condition of the spot weld of AHSS

- **Material**
  - **Base metal: DP590 1.0t, DP780 1.2t, DP980 1.2t**
  - **Lock plate: 590FB 3.2t**

Material	Yield Strength [MPa]	Tensile Strength [MPa]	Elongation [%]
DP590 1.0t	422.3	632.3	27.1
DP780 1.2t	544.4	861.7	22.6
DP980 1.2t	626.8	1004.2	12.9

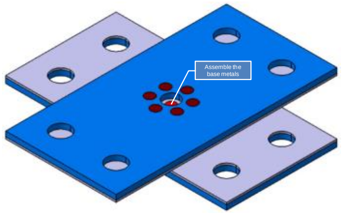
- **Specimen shape and fabrication**

Loading angle: 0°~75°

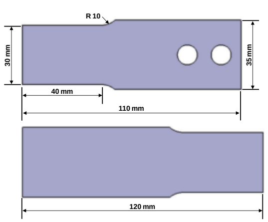


1. Spot welding between a base metal and a lock plate

2. Spot welding between the base metals attached the lock plate

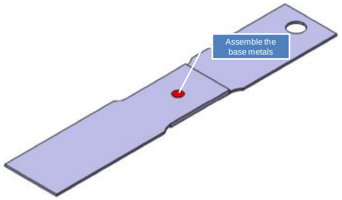


Loading angle: 90°



1. Dog-born shape specimen for a pure-shear test (Concentrate the plastic deformation around a spot weld)

2. Spot welding between the base metal (Failure test using the pure-shear jig set)



Failure test condition of the spot weld of AHSS

- **Spot welding condition**
  - **Apparatus: Static spot/projection welding machine**
  - **Set the spot welding conditions**
    - ✓ **After U-tension test, measuring the diameter of a nugget**
    - ✓ **Nugget diameter: $d \cong 5\sqrt{t}$**

Material	Squeeze Time [cycles,1/60sec]	Weld Time [cycles]	Hold Time [cycles]	Current [kA]		Force [kN]
				Base metals	Base metal & lock plate	
DP590 1.0t	20	15	20	8.3	7.8	3.0
DP780 1.2t	20	17	17	7.0	7.8	4.0
DP980 1.2t	20	17	17	7.4	8.2	4.0

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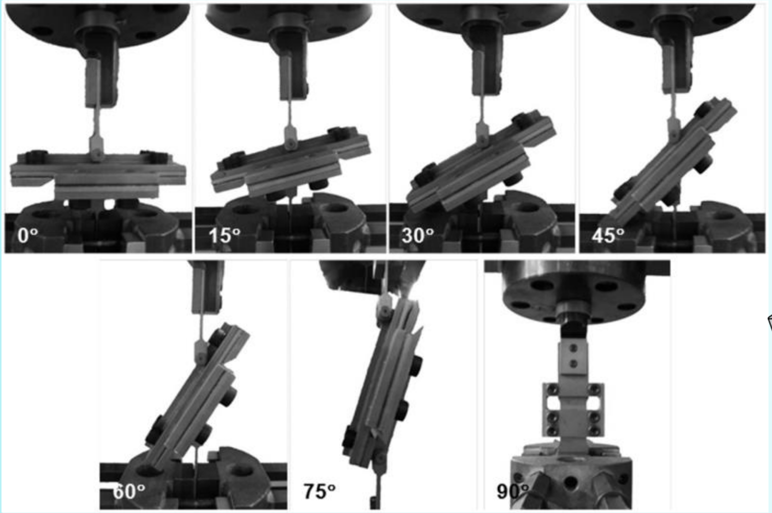
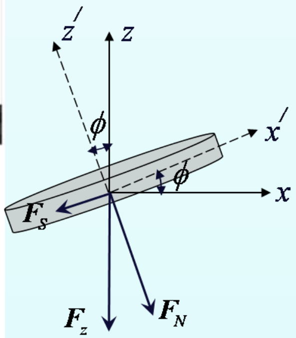
Failure test condition of the spot weld of AHSS

- **Failure tests under combined loading condition**





Decomposition of the failure load

$$F_N = F_z \cos\phi$$

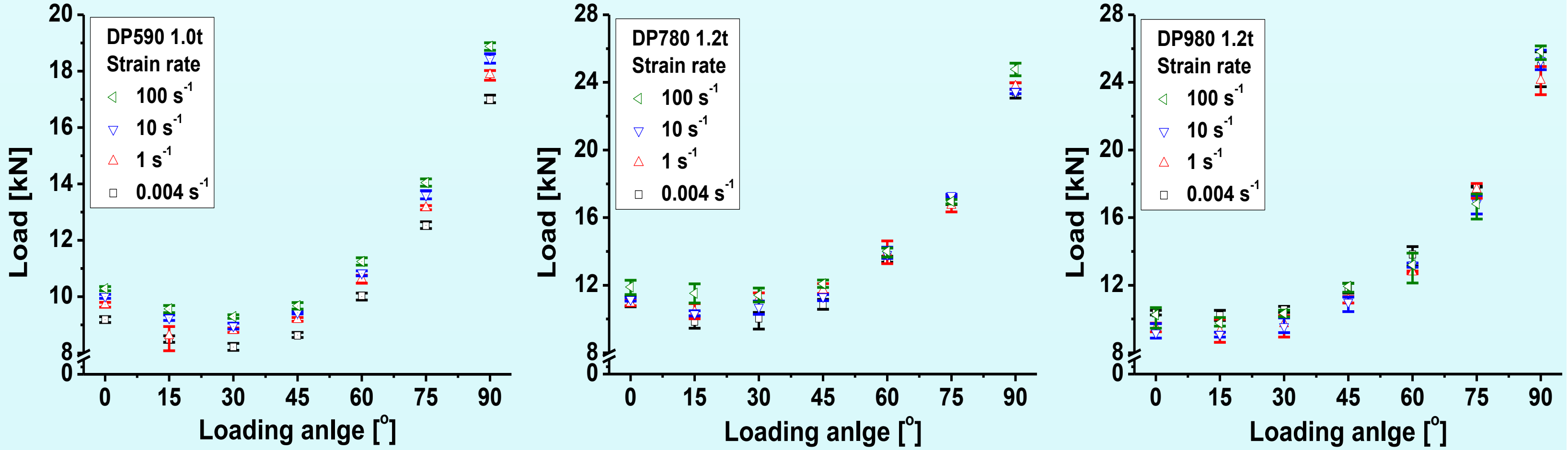
$$F_S = F_z \sin\phi$$

$$\frac{F_S}{F_N} = \frac{F_z \sin\phi}{F_z \cos\phi} = \tan\phi$$

Type	Testing Machine	Strain rate [/sec]	Crosshead speed [m/sec]	Loading angle [°]
Quasi-static	Instron 5583	0.004	5×10-5	0° 15° 30° 45° 60° 75° 90°
Dynamic	High Speed Material Testing Machine (HSMTM)	1	0.0125	
		10	0.125	
		100	1.25	

Experimental results

- **Failure load-loading angle curves of AHSS**
  - 0°~30°: maximum load decreases as the loading angle increases
  - 30°~90°: maximum load increases as the loading angle increases
  - Maximum load increases when the imposed strain rate increases.
    - Increase in the ratio of the failure load from 0.004 s^{-1} to 100 s^{-1}
      - DP590 1.0t increases by approximately 21%; DP780 1.2t increases by approximately 8.4%; DP980 1.2t increases by approximately 2.2%
    - Strain rate sensitivity of AHSS decreases as material grade increases
      - After spot welding, AHSS containing high carbon is more brittle than CQ and HSS



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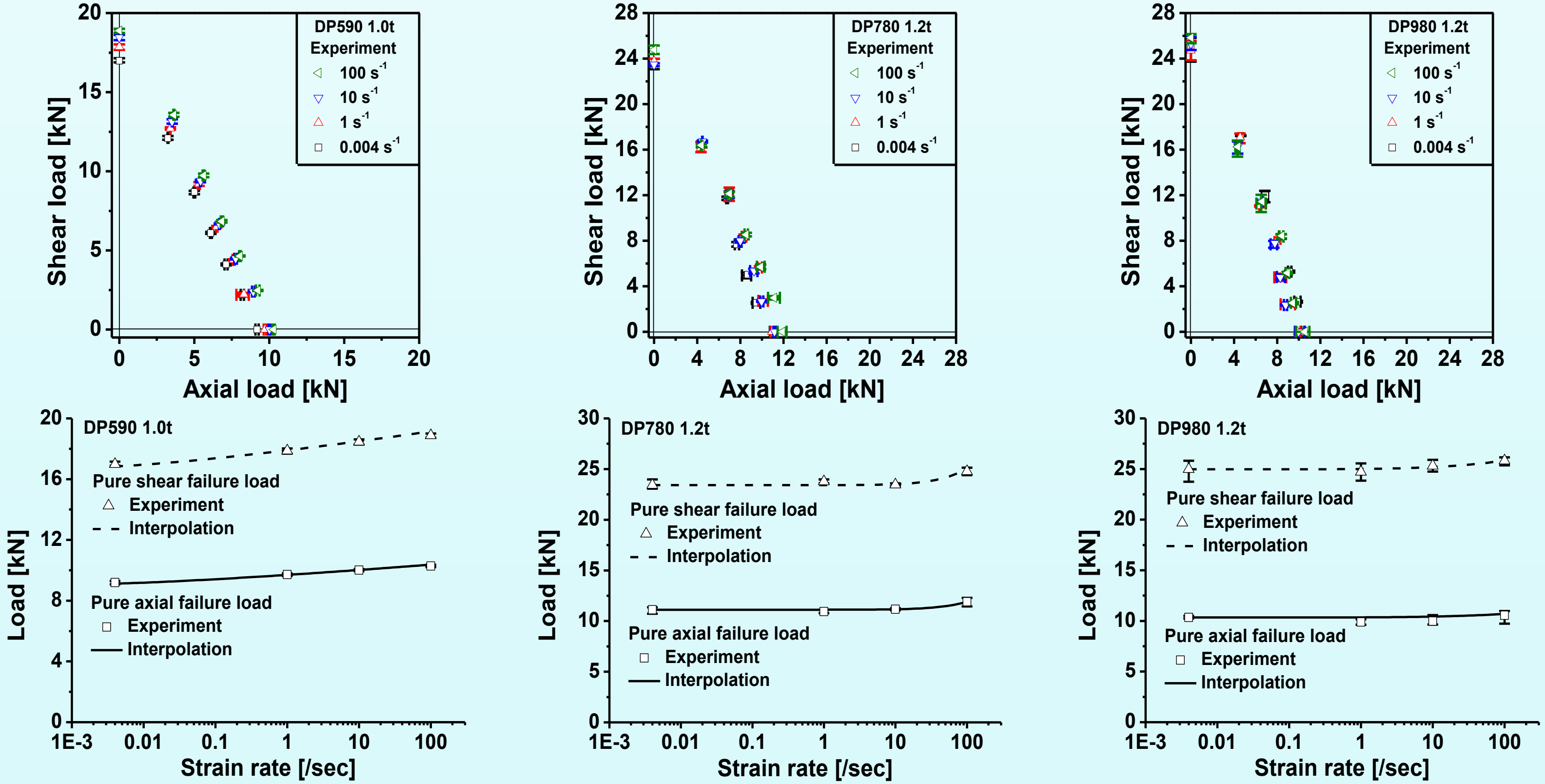
Experimental results

- **Failure contours of AHSS**
  - **Failure contour expands as the strain rate increases**
  - **Failure contours of a spot weld in DP790 1.2t and DP980 1.2t are less sensitive to the strain rate compared to those in DP590 1.2t.**



Dynamic failure model of spot welds

Conventional failure model of a spot weld

- **Failure model of a spot weld**
  - **Prediction of a failure of a spot weld for the structure analysis**
  - **Function of the axial force and the shear force acting on a spot weld**
  - **When a force acting on a spot weld is out of a failure contour, the finite element model of a spot weld is deleted**
  - **Not consider the dynamic effect on the failure charateristics**

Lee *et al.* (1998)

$$\left(\frac{f_n}{F_N}\right)^2 + \left(\frac{f_s}{F_S}\right)^2 = 1$$

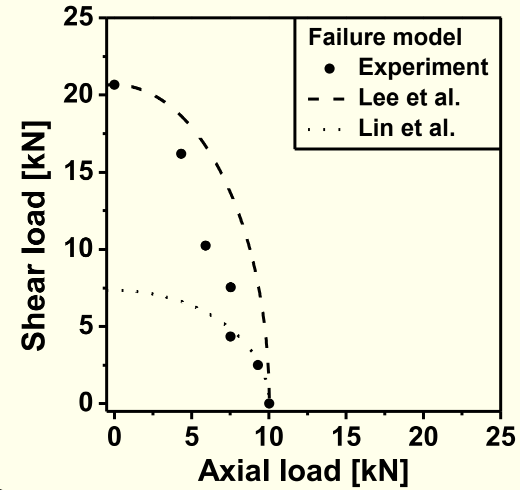
- Elliptic shape failure curve
- The most commonly used in a commercial code

Lin *et al.* (2003)

$$\left[1-2\alpha+2\alpha^2\right]\left(\frac{f_n}{\pi D t \tau_0}\right)^2 + \left[\frac{1}{3}+\left(\frac{4t}{\pi D}\right)\right]\left(k\frac{f_s}{\pi D t \tau_0}\right)^2 = 1$$

- Approximation of the failure of a spot weld through the axial failure force acting on a spot weld
- Decrease of the failure load with increasing the loading angle

Failure contour



* **B. Langrand & C. Combescure (2004)**

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Dynamic failure model of a spot weld

- **Dynamic failure model of a spot weld under combined loading condition**

Dynamic failure model

$$\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2+\beta\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)\left(\frac{f_s}{F_S(\dot{\varepsilon})}\right)+\left(\frac{f_s}{F_S(\dot{\varepsilon})}\right)^2=1$$

$$F_N(\dot{\varepsilon})=F_{N_0}\left(1+C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^p\right)$$

$$F_N(\dot{\varepsilon})=F_{S_0}\left(1+C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^p\right)$$

F_{N_0} : Quasi-static axial failure load

F_{S_0} : Quasi-static shear failure load

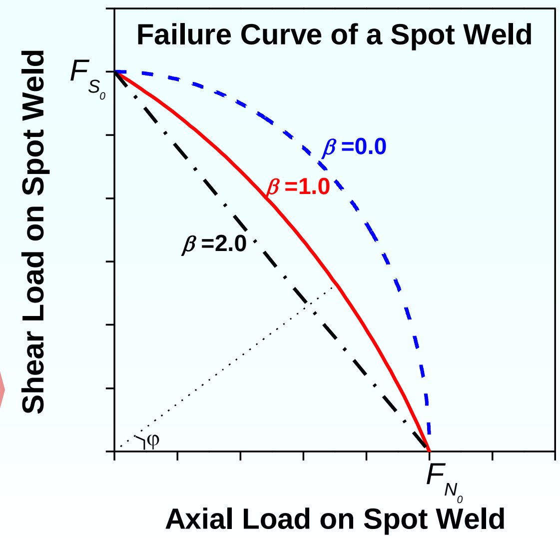
β : Shape parameter

C, p: Strain-rate sensitivity parameter

$\dot{\varepsilon}_0$: Reference strain-rate (quasi-static)

- **The shape of a failure contour determined by the *β***
  - ***β* = 0 : Elliptic shape**
  - **0< *β* <2 : *β*-norm* shape**
  - ***β* = 2 : Linear curve**

** H. Huh (1986); H. Huh & W. H. Yang (1991)*



$$\varphi=\frac{1}{2}\tan^{-1}\frac{\beta F_N F_S}{F_S^{\,2}-F_N^{\,2}}$$

$$F_{\min}=\frac{\sqrt{2}F_N F_S}{\sqrt{F_S^{\,2}+F_N^{\,2}+\sqrt{F_S^{\,4}+F_N^{\,4}-(2-\beta^2)F_N^{\,2}F_S^{\,2}}}}$$

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Construction of a failure model

Development of dynamic failure model of spot welds

- **Determination of shape parameter β – DP590 1.0t**

$$\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2 + \beta\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)\left(\frac{f_s}{F_S(\dot{\varepsilon})}\right) + \left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2 = 1$$

$$F_N(\dot{\varepsilon}) = F_{N_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref.}}\right)^p\right)$$

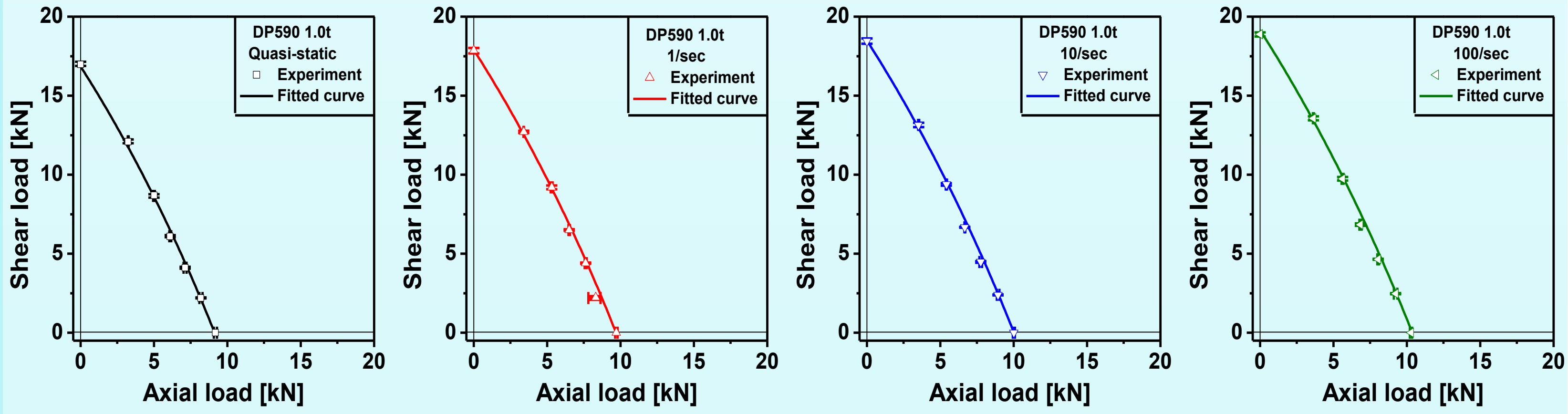
$$F_S(\dot{\varepsilon}) = F_{S_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref.}}\right)^p\right)$$

where F_{N_0} and F_{S_0} are failure loads

under the quasi-static loading condition, $\dot{\varepsilon}_{ref.} = 0.004/\mathrm{sec}$

Interpolated failure criterion of a spot weld of DP590 1.0t at each strain rate

Strain-rate	F_N [kN]	F_S [kN]	β
Quasi-static	9.13	16.85	1.57
1/sec	9.70	17.90	
10/sec	10.02	18.50	
100/sec	10.37	19.14	



Development of dynamic failure model of spot welds

- **Determination of shape parameter β – DP780 1.2t**

$$\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2 + \beta\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)\left(\frac{f_s}{F_S(\dot{\varepsilon})}\right) + \left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2 = 1$$

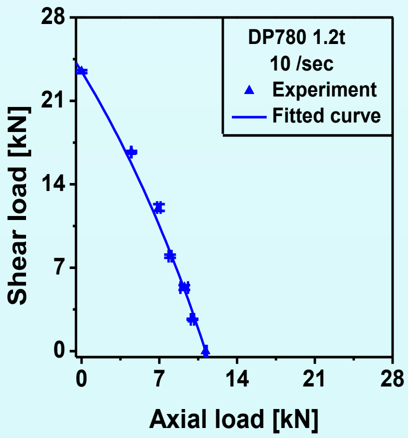
$$F_N(\dot{\varepsilon}) = F_{N_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref.}}\right)^p\right)$$

$$F_S(\dot{\varepsilon}) = F_{S_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref.}}\right)^p\right)$$

where F_{N_0} and F_{S_0} are failure loads under the quasi-static loading condition, $\dot{\varepsilon}_{ref.} = 0.004/\mathrm{sec}$

Interpolated failure criterion of a spot weld of DP780 1.2t at each strain rate

Strain-rate	F_N [kN]	F_S [kN]	β
Quasi-static	11.12	23.42	1.44
1/sec	10.94	23.77	
10/sec	11.17	23.46	
100/sec	11.90	24.77	



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Development of dynamic failure model of spot welds

- **Determination of shape parameter β – DP980 1.2t**

$$\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2+\beta\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)\left(\frac{f_s}{F_S(\dot{\varepsilon})}\right)+\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2=1$$

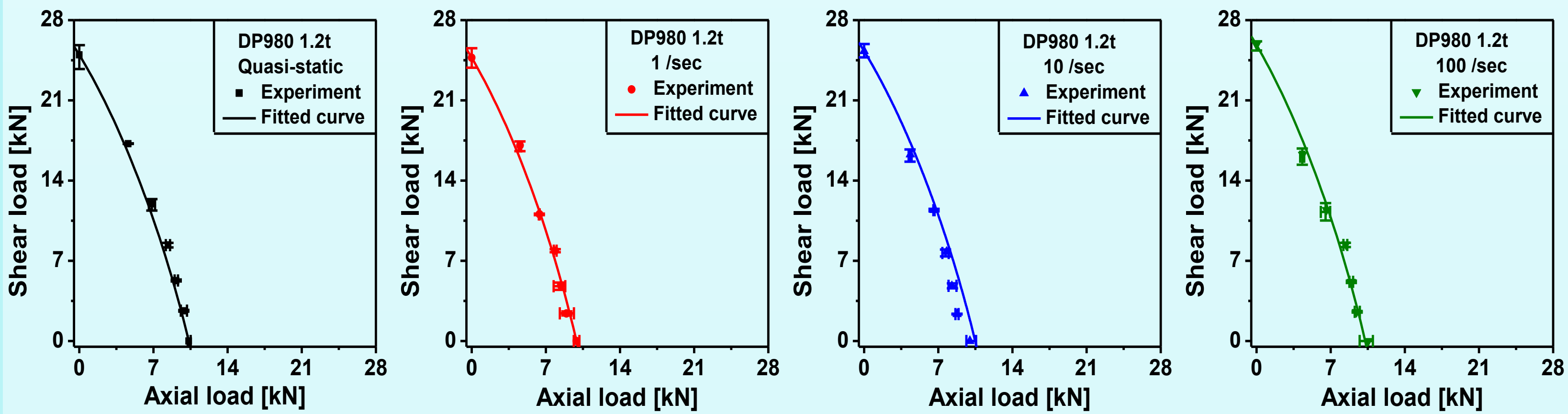
$$F_N(\dot{\varepsilon})=F_{N_0}\left(1+C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref.}}\right)^p\right)$$

$$F_S(\dot{\varepsilon})=F_{S_0}\left(1+C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref.}}\right)^p\right)$$

where F_{N_0} and F_{S_0} are failure loads under the quasi-static loading condition, $\dot{\varepsilon}_{ref.}=0.004/\text{sec}$

Interpolated failure criterion of a spot weld of DP980 1.2t at each strain rate

Strain-rate	F_N [kN]	F_S [kN]	β
Quasi-static	10.34	24.97	1.26
1/sec	9.89	24.71	
10/sec	10.48	25.30	
100/sec	10.26	25.83	



Development of dynamic failure model of spot welds

- **Strain rate sensitivity curve of pure-shear failure load and axial failure load**
  - **Determination of rate sensitivity parameter C and p**
  - **Strain sensitivity of failure load decrease as the strain rate increases**

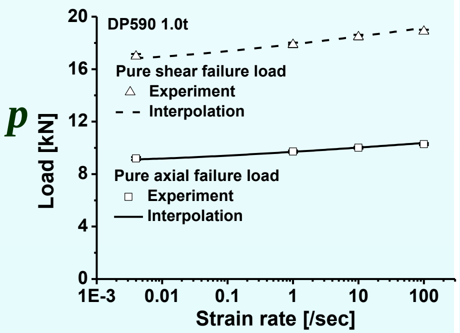
$$\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2 + \beta\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)\left(\frac{f_s}{F_S(\dot{\varepsilon})}\right) + \left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2 = 1$$

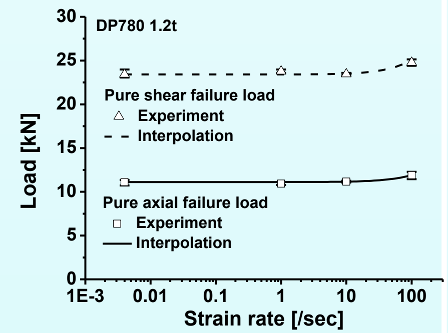
$$F_N(\dot{\varepsilon}) = F_{N_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref.}}\right)^p\right),\quad F_S(\dot{\varepsilon}) = F_{S_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref.}}\right)^p\right)$$

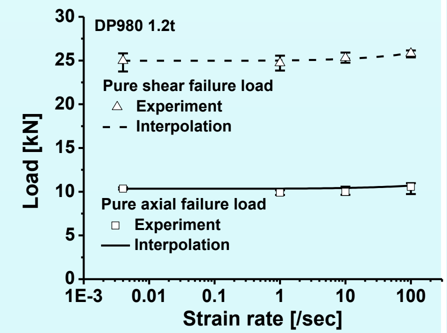
where F_{N_0} and F_{S_0} are failure loads

under the quasi-static loading condition, $\dot{\varepsilon}_{ref.} = 0.004\,/\,\mathrm{sec}$

Material	F_{N_0} [kN]	F_{S_0} [kN]	β	C	p
DP780 1.0t	9.13	16.92	1.57	0.00683	1.2925
DP780 1.2t	11.12	23.42	1.44	3.60×10^{-13}	11.22515
DP980 1.2t	10.34	24.97	1.26	1.79×10^{-7}	5.26177







Dynamic failure model for spot welds of AHSS

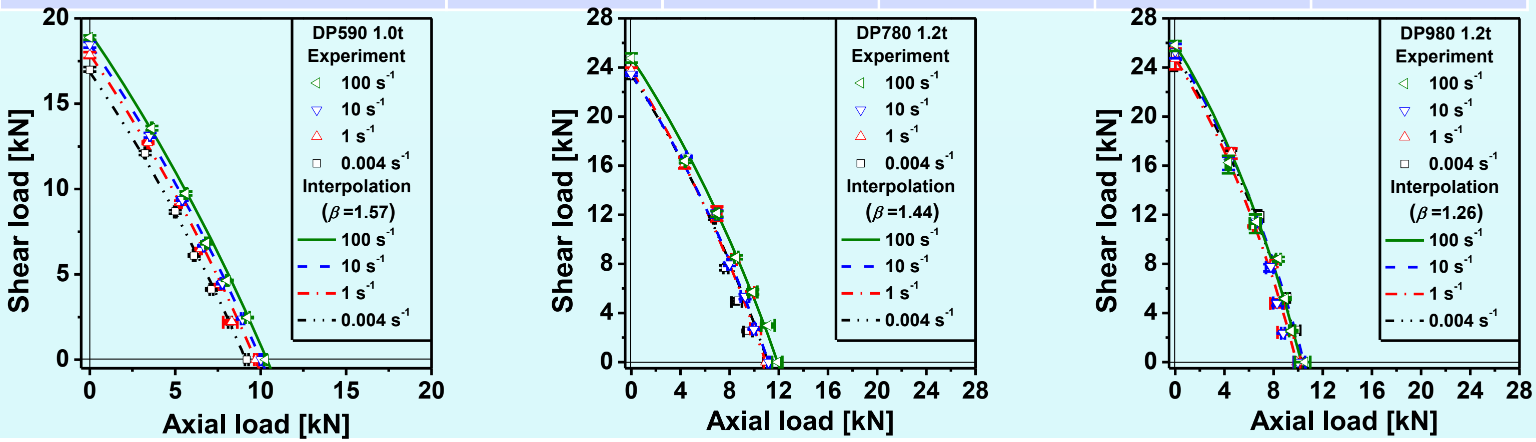
- **Coefficients of the dynamic failure model of spot welds**

$$\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2 + \beta\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)\left(\frac{f_s}{F_S(\dot{\varepsilon})}\right) + \left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2 = 1$$

$$F_N(\dot{\varepsilon}) = F_{N_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref.}}\right)^p\right),\ F_S(\dot{\varepsilon}) = F_{S_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref.}}\right)^p\right)$$

where F_{N_0} and F_{S_0} are failure loads under the quasi-static loading condition, $\dot{\varepsilon}_{ref.} = 0.004/\mathrm{sec}$

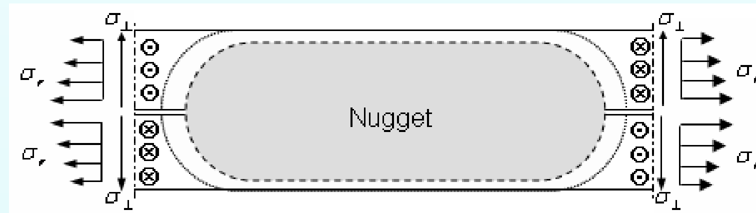
Material	F_{N_0} [kN]	F_{S_0} [kN]	β	C	p
DP780 1.0t	9.13	16.92	1.57	0.00683	1.2925
DP780 1.2t	11.12	23.42	1.44	3.60×10^{-13}	11.22515
DP980 1.2t	10.34	24.97	1.26	1.79×10^{-7}	5.26177



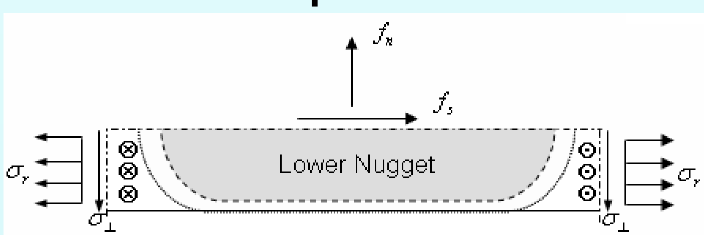
Failure Model:
background & verification

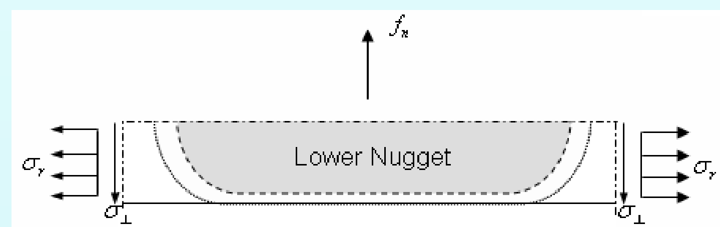
Failure Model of the Spot Weld under Combined Load

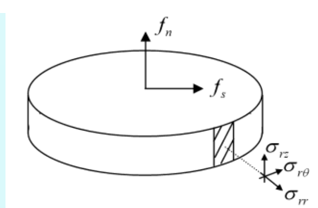
- **General Stress Field of the Spot Weld under Combined Axial and Shear load**

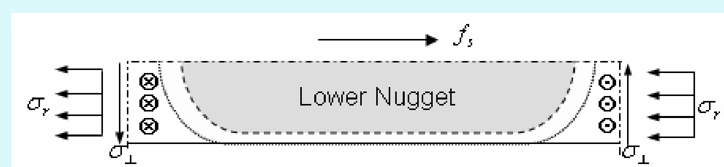


- **Simplification of the stress field near the spot weld**
  - ✓ Nugget has cylinder shape
  - ✓ Uniform stress distribution through the thickness
  - ✓ Decomposition of stress field with axial and shear load









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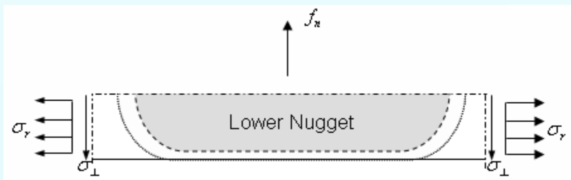
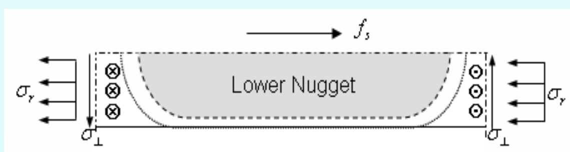
Failure Model of the Spot Weld under Combined Load

- **From the Decomposed Stress Field,**



Under axial loading

$$\sigma_{rr} = k\frac{f_n}{t^2},\ \sigma_{rz} = -\frac{f_n}{2\pi rt}$$



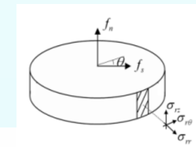
Under shear loading

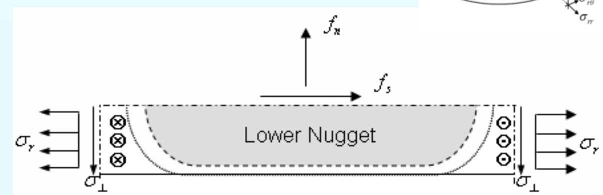
$$\sigma_{rr} = -\frac{f_s}{\pi rt}\cos^3\theta,\ \sigma_{\theta\theta} = -\frac{f_s}{\pi rt}\cos\theta\sin^2\theta$$

$$\sigma_{r\theta} = \frac{f_s}{\pi rt}\sin\theta\cos^2\theta$$

$$\sigma_{rz} = \frac{f_s}{2\pi r^2}\cos\theta,\ \sigma_{\theta z} = -\frac{f_s}{2\pi r^2}\sin\theta$$

r: radius of the nugget
t : thickness of the nugget





Under combined axial and shear loading

$$\sigma_{rr} = -\frac{f_s}{\pi rt}\cos^3\theta + k\frac{f_n}{t^2}$$

$$\sigma_{\theta\theta} = -\frac{f_s}{\pi rt}\cos\theta\sin^2\theta$$

$$\sigma_{r\theta} = \frac{f_s}{\pi rt}\sin\theta\cos^2\theta$$

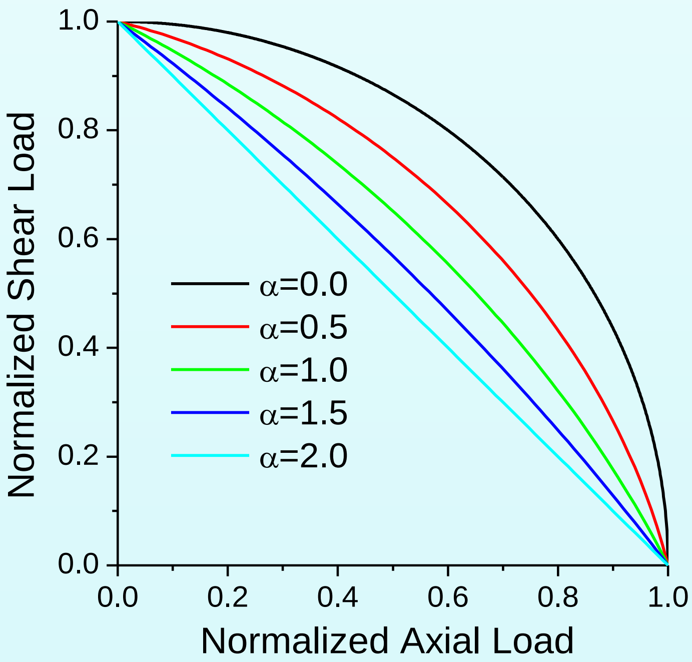
$$\sigma_{rz} = \frac{f_s}{2\pi r^2}\cos\theta - \frac{f_n}{2\pi rt}$$

$$\sigma_{\theta z} = -\frac{f_s}{2\pi r^2}\sin\theta$$

Failure Model of the Spot Weld under Combined Load

- **Modified Failure Model**
  - **From von-Mises criterion**

$$\sigma_{rr}^2 - \sigma_{rr}\sigma_{\theta\theta} + \sigma_{\theta\theta}^2 + 3\sigma_{r\theta}^2 + 3\sigma_{rz}^2 + 3\sigma_{\theta z}^2 = \sigma_0^2 \Rightarrow \left(\frac{f_n}{F_N}\right)^2 + \alpha\left(\frac{f_n}{F_N}\right)\left(\frac{f_s}{F_S}\right) + \left(\frac{f_s}{F_S}\right)^2 = 1$$



where, F_N : Axial failure load of the spot weld

$$F_N = 2\pi r t \sigma_0(\dot{\varepsilon}) g_1\left(\frac{t}{r}\right)$$

F_S : Shear failure load of the spot weld

$$F_S = 2\pi r t \sigma_0(\dot{\varepsilon}) g_2\left(\frac{t}{r}\right)$$

$$\Downarrow$$

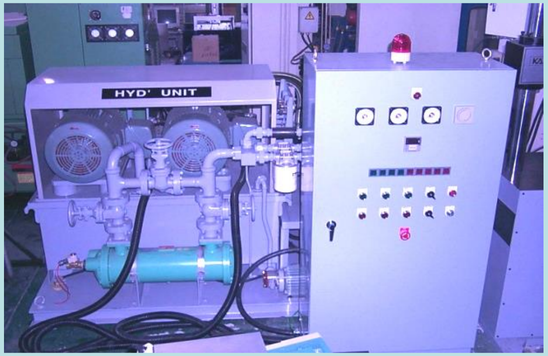
$$\overline{N}^2 + \alpha(\dot{\varepsilon})\overline{N}\,\overline{S} + \overline{S}^2 = 1 \qquad (0 < \alpha < 2)$$

where, $\overline{N}$: Normalized axial load of the spot weld

$\overline{S}$: Normalized shear load of the spot weld

Extension to the Dynamic Failure of Spot Weld

- **Dynamic Test using High Speed Material Testing Machine**
  - **High Speed Material Testing machine**
    - ✓ **Dynamic material properties at intermediate strain rates**
    - ✓ **Servo-hydraulic system**
    - ✓ **Max. speed: 7,800 mm/s**
    - ✓ **Max. load: 30 kN**
    - ✓ **Range of strain rate: 0.1 ~ 500/sec**

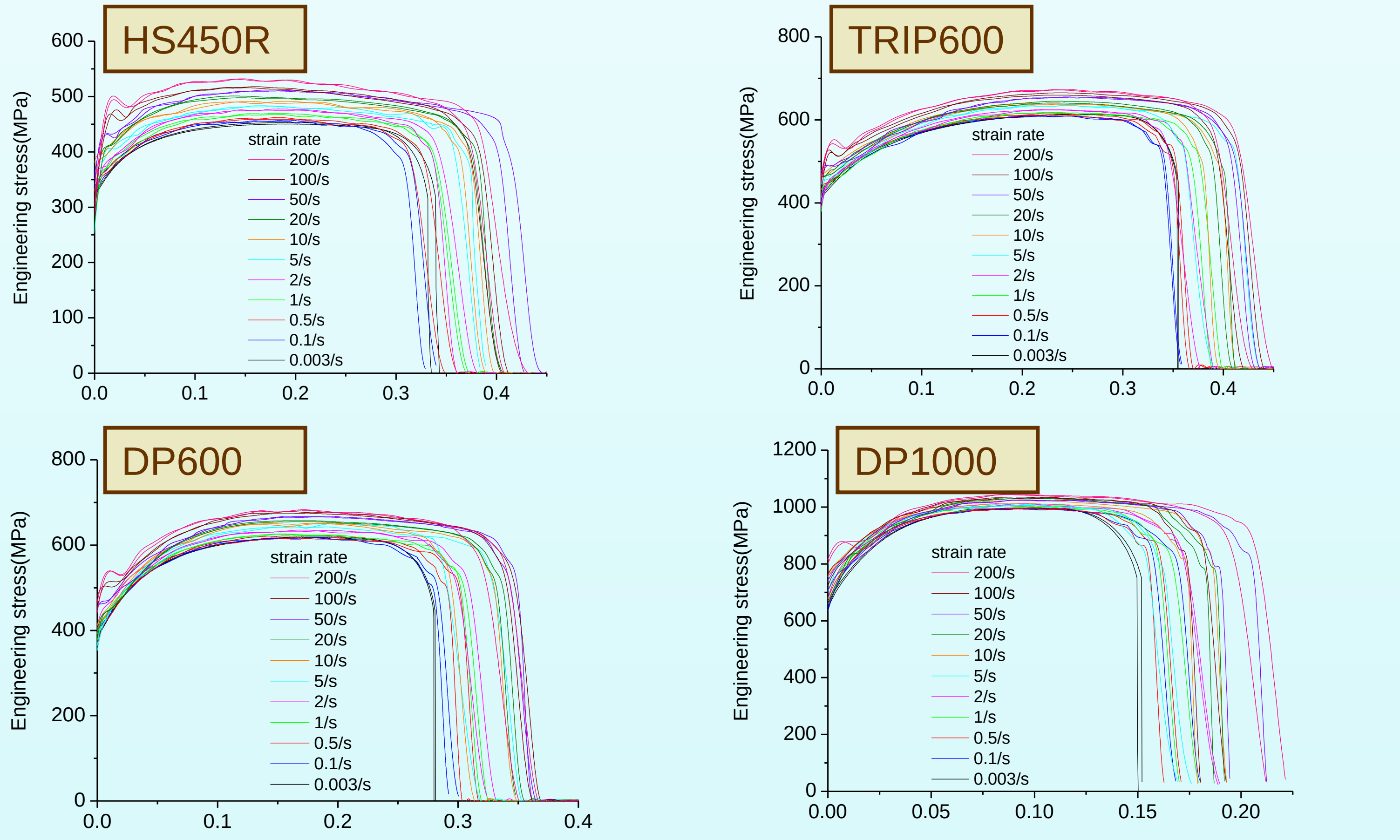


Hydraulic Unit

Testing Machine

Extension to the Dynamic Failure of Spot Weld

- **Dynamic Test using High Speed Material Testing Machine**



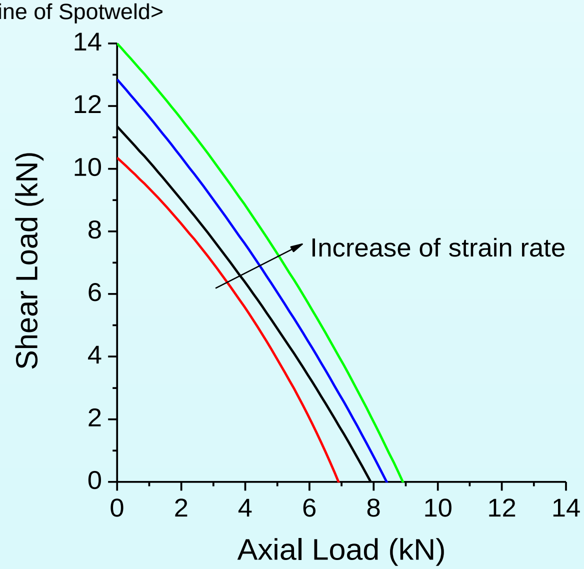
Extension to the Dynamic Failure of Spot Weld

- **Specimens, Jig, Testing Machine**

Fixture is attached to HSMTM

Rate-dependent failure model

$$\left(\frac{f_n}{F_N}\right)^2 + \alpha\left(\frac{f_n}{F_N}\right)\left(\frac{f_s}{F_S}\right) + \left(\frac{f_s}{F_S}\right)^2 = 1$$



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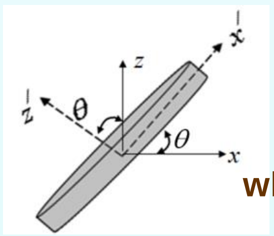
Failure Model of the Spot Weld under Combined Load

Failure Curve of the Spot Weld

- **Material:SPRC340R 1.2t**



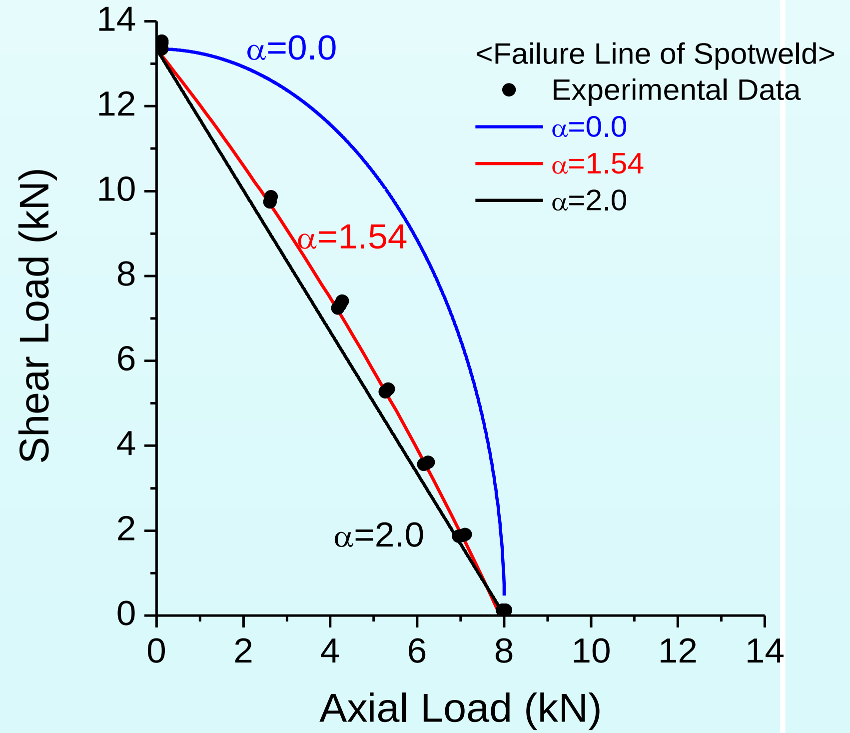
Axial load: $F_N = F\cos\theta$

Shear load: $F_S = F\sin\theta$

where θ is initial inclined angle

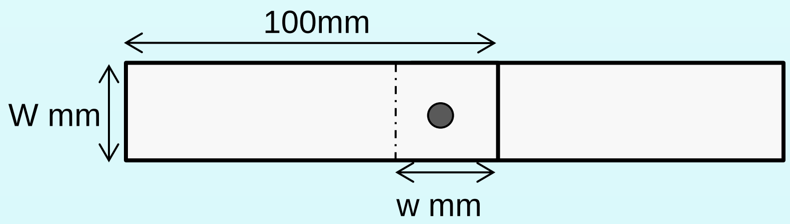
Run no.	Inclined angle (˚)	Failure load (kN)
01,02,03	0	8.025, 8.037, 7.968
04,05,06	15	7.286, 7.361, 7.204
07,08,09	30	7.134, 7.219, 7.113
10,11,12	45	7.462, 7.453, 7.542
13,14,15	60	8.448, 8.364, 8.553
16,17,18	75	10.21, 10.09, 10.41
19,20,21	90	13.35, 13.48, 13.57

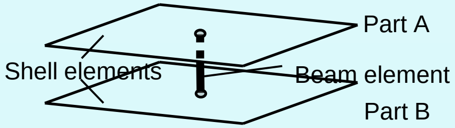
$$\left(\frac{f_N}{7.97}\right)^2 + \alpha\left(\frac{f_N}{7.97}\right)\left(\frac{f_S}{13.35}\right) + \left(\frac{f_S}{13.35}\right)^2 = 1$$



Application to FE Analysis of Lap-Shear Tests

- **Lap-Shear Tests of the Spot Weld**
  - **Combined axial and shear load is applied on the spot weld**
  - **The ratio of axial to shear load acting on the spot weld depends on the width of the specimen**
    - ✓ **Width of specimen: 30 mm, 40 mm**
  - **Spot weld is modeled with beam element and Base metal is modeled with shell element whose size is 8 mm**
  - **Failure load of spot weld obtained from the analysis is compared with the one obtained from the experiment**





$$\left(\frac{f_N}{7.97}\right)^2 + 1.54\left(\frac{f_N}{7.97}\right)\left(\frac{f_S}{13.35}\right) + \left(\frac{f_S}{13.35}\right)^2 = 1$$

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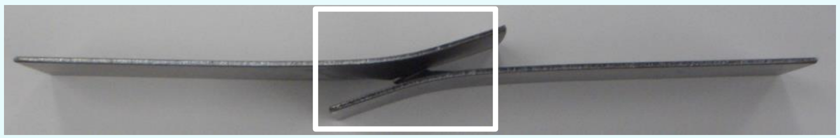
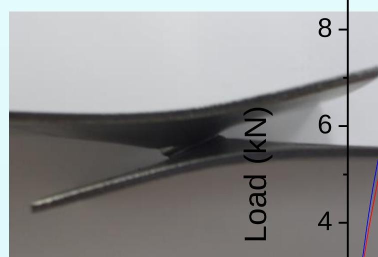
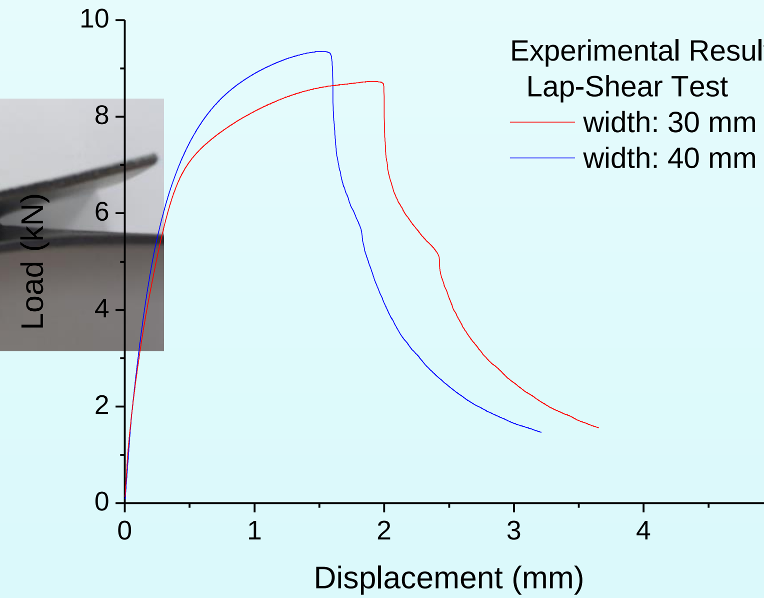
Application to FE Analysis of Lap-Shear Tests

- **Experimental Results**

Width: 40 mm



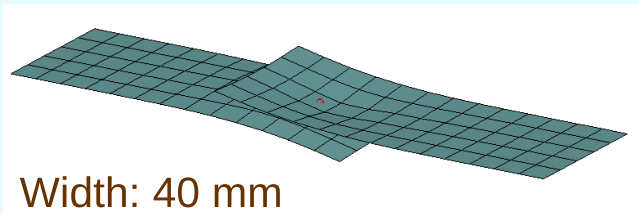


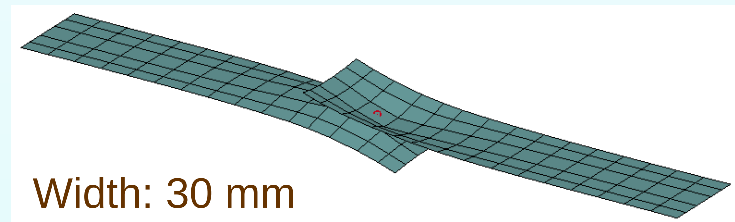


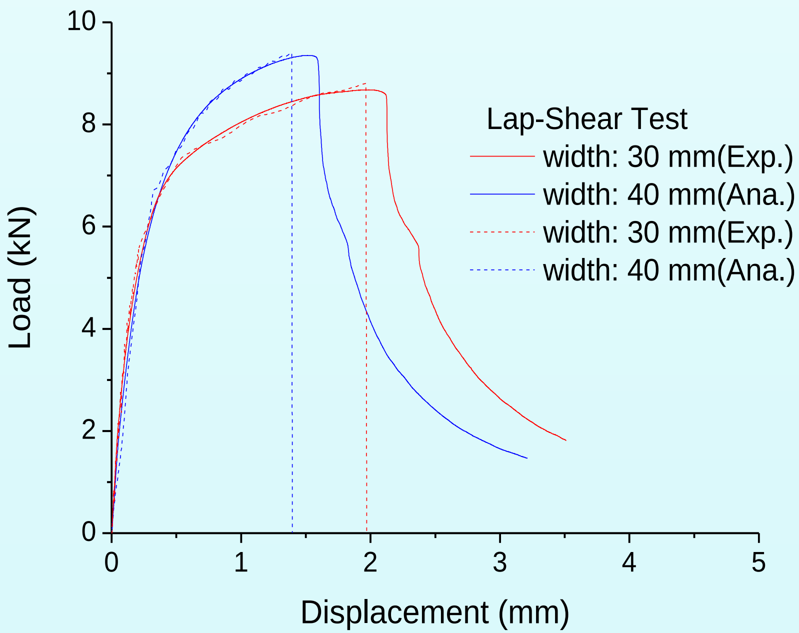
Width: 30 mm

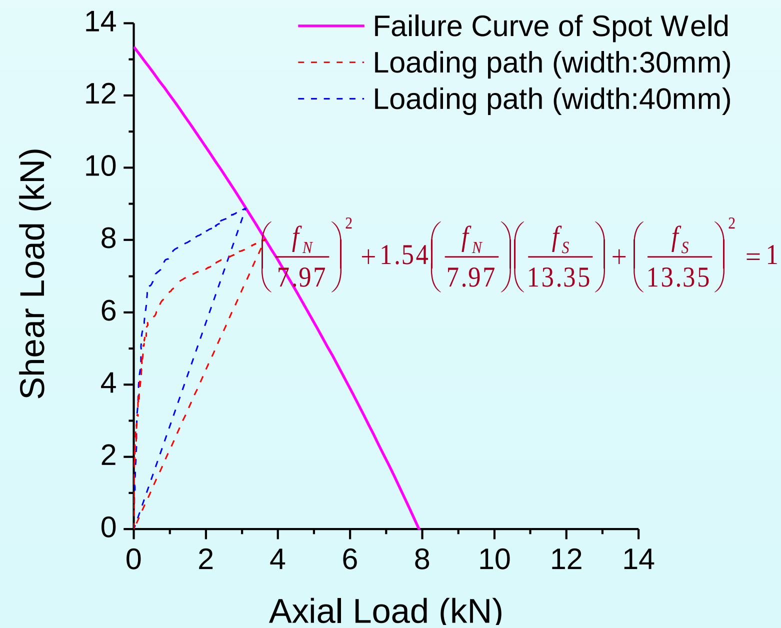
Application to FE Analysis of Lap-Shear Tests

- **Comparison of the Analysis Result**









Summary

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Summary

- **Design the fixture and the specimen for failure tests of the spot weld to avoid nugget rotation and remove the moment.**
- **Investigate the failure characteristics and the failure criterion of a spot weld of AHSS under dynamic combined loading condition**
  - **Dynamic failure tests of spot welds in DP steel sheets were conducted at seven different combined loading conditions in order to obtain the dynamic failure loads of spot welds.**
  - **The maximum load for spot welds in DP steel sheets increases when the imposed strain rate increases.**
  - **A dynamic failure model was proposed after analyzing the experimental data.**
  - **The proposed failure model has the shape of a β-norm with the strain-rate sensitivity values of the failure load for an exponential function of the logarithm of the strain-rate.**

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Failure Tests and Modeling of the Laser Weld under Combined Loading Condition

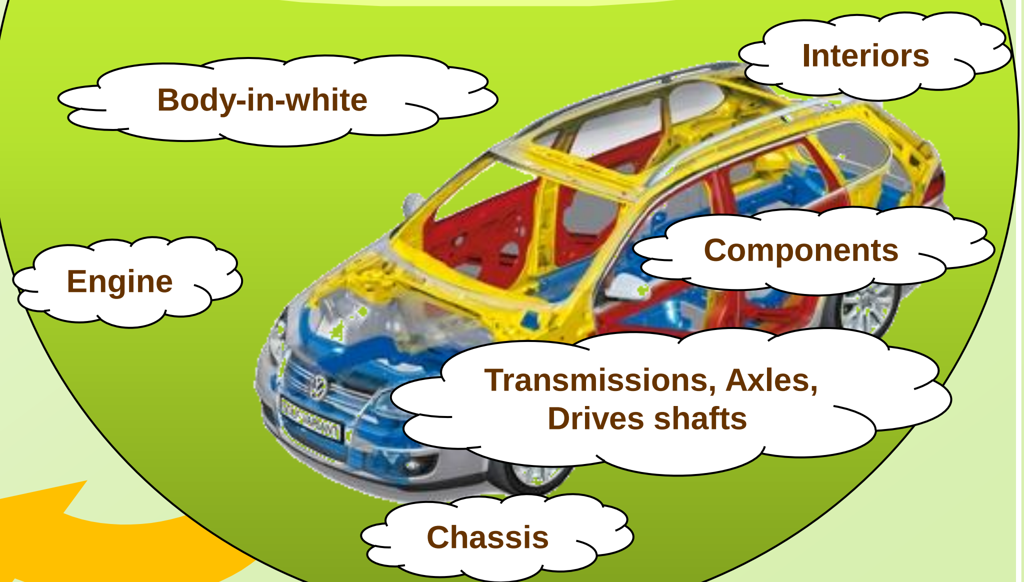
Laser welding in the automotive industry

Audi 100 (1968~1994)
The first application of laser welding for assembly process of Audi 100 model in 1968

Application of laser welding in auto-body

Application in BIW

Roof side rail, Trunk lid, UB-side, Side panel, B-pillar, Front module, Hood, etc.



Advantages of laser welding

- Reduction of facility investment cost
- Improvement of productivity
- Improvement of design freedom
- Improvement of crashworthiness

Motivation (1/3)

- **Application of laser welding to improve the stiffness of BIW**
  - **C70 model of Volvo: increase in the application of laser welding**
  - **Audi: laser welding length of Q7, TT and A6 models are 4.4 m, 5.3 m and 14.2 m, respectively**
  - **G35 model of Nissan: improve the stiffness of BIW after the application of laser welding**
- **Evaluation of crashworthiness in the design phase**

Prediction of the failure of laser welds in the design phase

Design change

Improvement of crashworthin ess

Safety Design

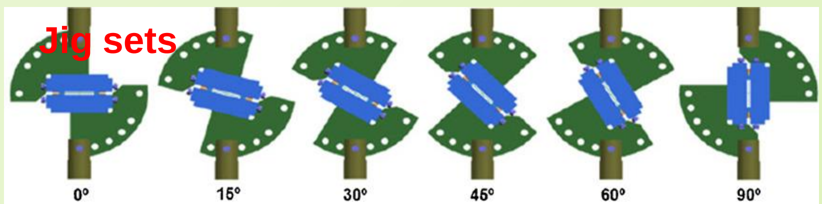
Failure characteristics of laser welds?

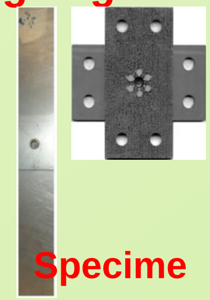
Understanding of the failure characteristics of laser welds

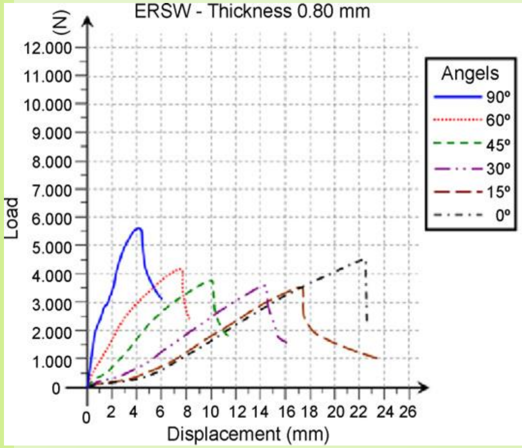
- Compatible FE modeling of laser welds
- Secure a reasonable failure criterion of laser welds through the failure test
- Approximate the experimental results through a failure criterion

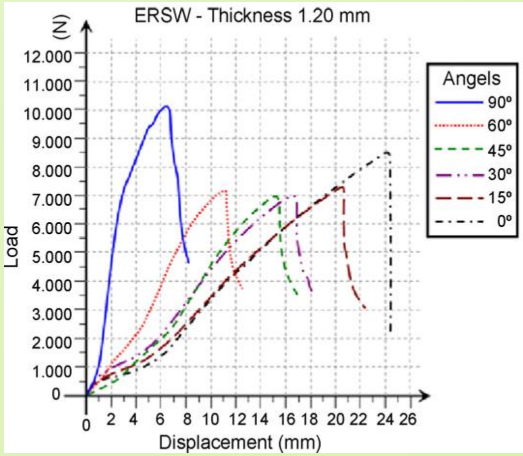
Motivation (2/3)

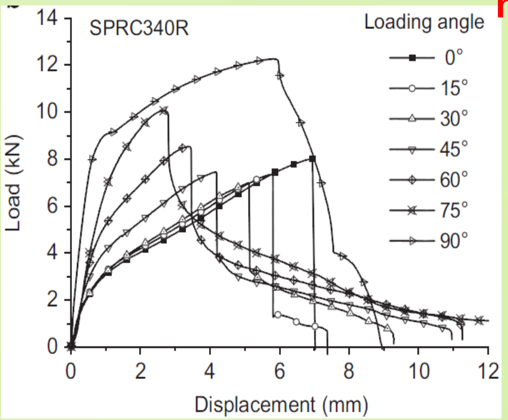
- **Failure tests of laser welds w.r.t. loading angle**
  - **Rotation of weldment when the impact load is applied to the weldment → Change in the failure characteristics of laser welds and the deformed shape of a structure**
  - **Need for study on the failure tests of laser welds w.r.t. loading angle**









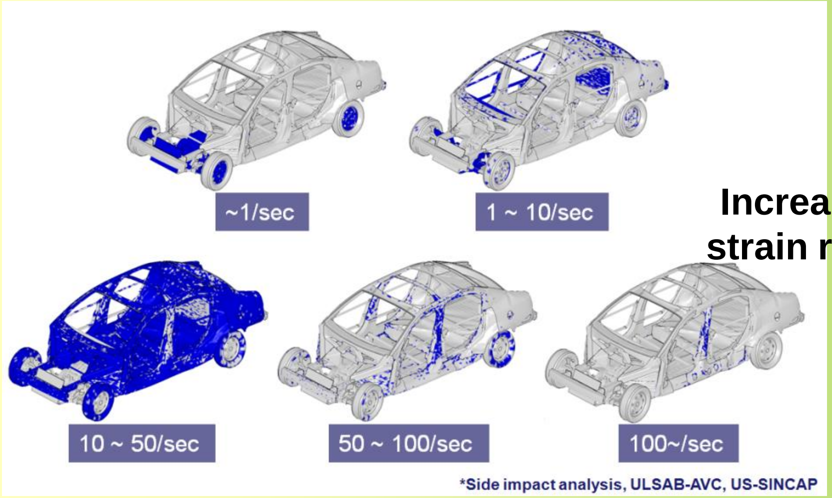


Kavamura & Batalha (2008)

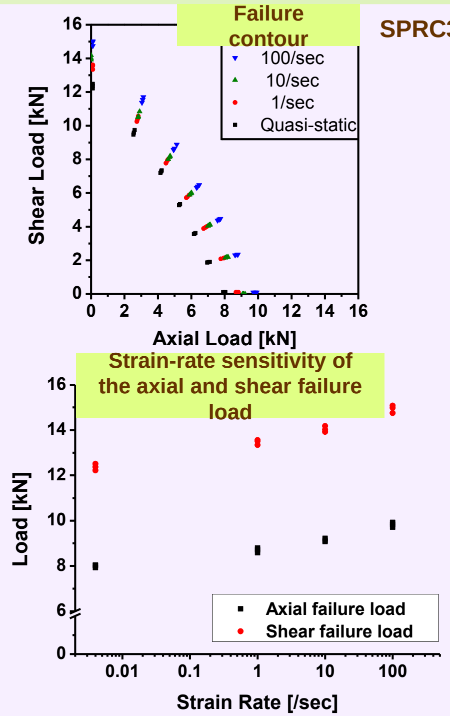
Song & Huh (2008, 2011)

Motivation (3/3)

- **Failure tests of laser welds w.r.t. strain rate**
  - **In case of spot welds, failure load increases and failure contour is extended with an increase of strain rate**
  - **Need for study on the failure tests of laser welds w.r.t. strain rate**



Increase strain rate



Song et al. (2008)

The effect of strain rate on the failure characteristics of laser welds?

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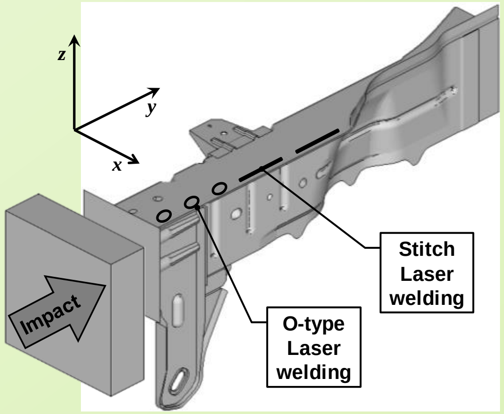
Research objective and scope

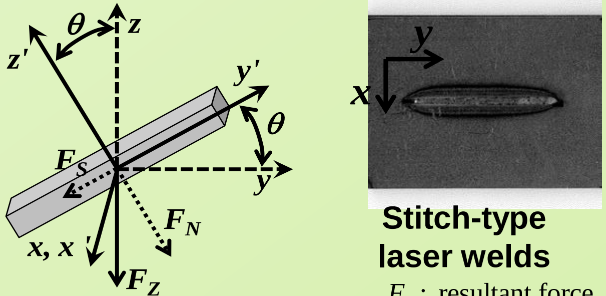
- **Research objective**
  - **Proposal of a new dynamic failure criterion for laser-welded regions under combined normal and shear loading conditions**
- **Research scope**
  - **Dynamic failure tests of laser welds under combined loading condition**
    - ✓ **A new jig system to prevent rotation of the bead during failure tests**
    - ✓ **Dynamic failure tests of laser welds w.r.t. strain rate**
    - ✓ **Acquisition of the failure loads and the failure contours of laser welds w.r.t. strain rate**
  - **Proposal of a new dynamic failure criterion for laser welds**
    - ✓ **Dynamic failure criterion considering a change in the failure mode of laser welds**
    - ✓ **Dynamic failure criterion considering a change in the failure loads w.r.t. the strain rate**
    - ✓ **Interpolation of the failure contour of laser weld with the dynamic failure model proposed**

Jig system for failure tests of laser welds under combined loading conditions

Selecting an object of study

- **Component and bead shape for study**
  - **Component: front side member**
  - **Bead shape: stitch-shape laser weld of 25 mm on SPRC340 1.2t**
    - ✓ **Frontal crash load is parallel to the longitudinal direction of laser welds**
      - – Consider the rotation of a bead by deformation of a component when the impact load is parallel to the longitudinal direction of laser welds





$$F_N = F_Z \cos\theta$$
$$F_S = F_Z \sin\theta$$

F_Z : resultant force
F_N : normal force
F_S : shear force
θ: rotation angle of a bead

Crash scenario of the front side member

Definition of the relative position of the external load and the bead

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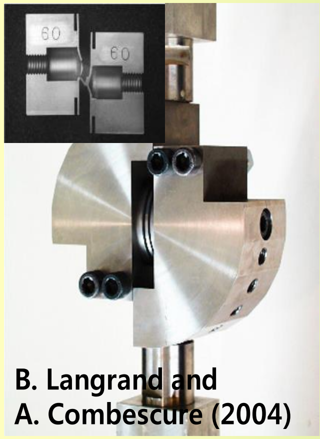
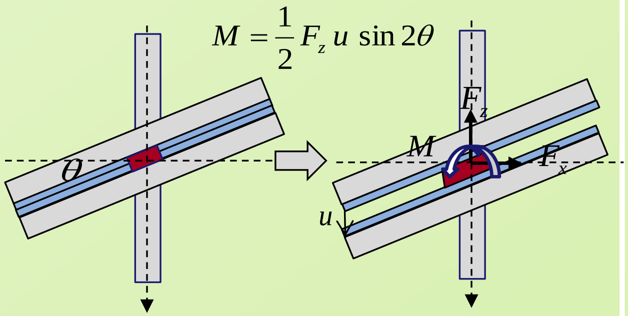
Test method under the combined loading condition

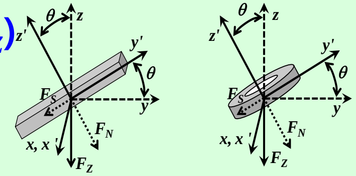
- **Failure test jig system under the combined loading condition**
  - Employment of jig systems to apply loading angles to the weldment
  - Conventional specimen: initiation of rotation of laser welds by the plastic deformation of the base metal around a bead
    - ✓ Impossible to apply a constant shear to normal load ratio to laser welds



Failure tests jig system under the combined loading condition



Normal (F_N) and shear (F_S) failure load are decomposed from the failure load (F_Z)



- Normal: $F_N = F_Z \cos\theta$
- Shear: $F_S = F_Z \sin\theta$

  θ : initial loading angle

* Impossible to calculate normal and shear failure loads from the failure loads with an initial loading alone

Specimen design for normal and shear loading condition

- **Specimen design to keep the initial loading angle**
  - **Spot welds: assembling the guide plate and the base metal**
  - **Laser welds: object for measuring the failure loads**

Design considerations

1. Dimensions of the silt in the guide plate

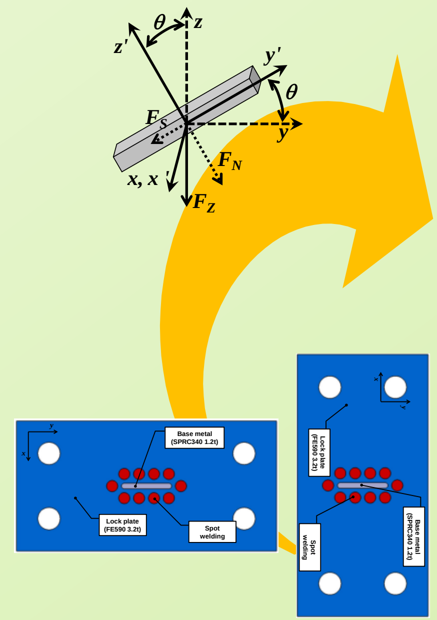
✓ Considering the length and the width of a bead as well as the width of the heat-affected zone (HAZ) generated by the laser welding process

✓ ***The width and the length of the slit are 3 mm and 27 mm, respectively***

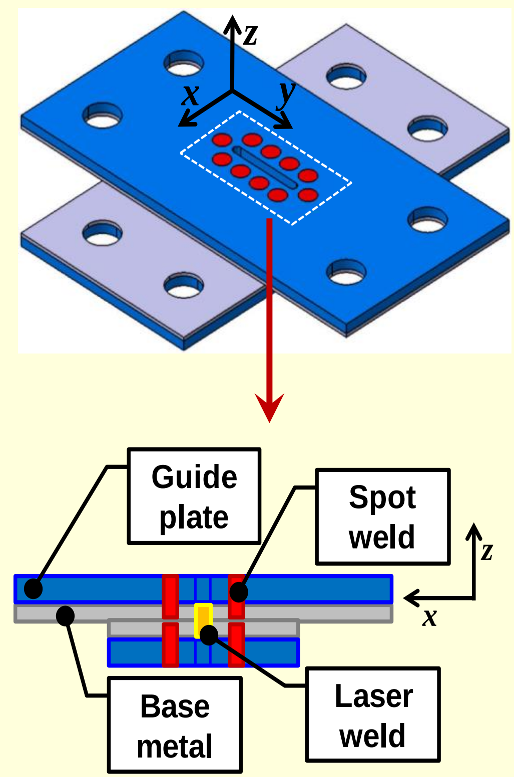
2. Location and interval of spot welds

✓ The radius of the influence of spot welds is approximately 3.75 mm.

✓ **The distance from the longitudinal axis of the bead to the center of a spot weld was set at 6.5 mm to eliminate the influence of the spot welds**



Assembled specimen of base metal and guide plate



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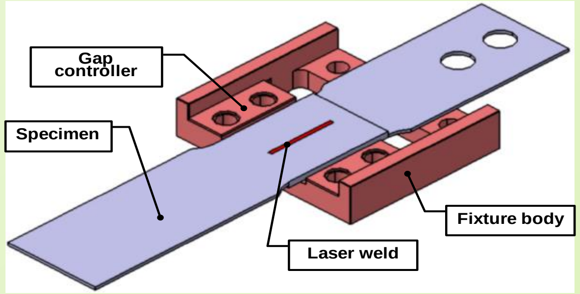
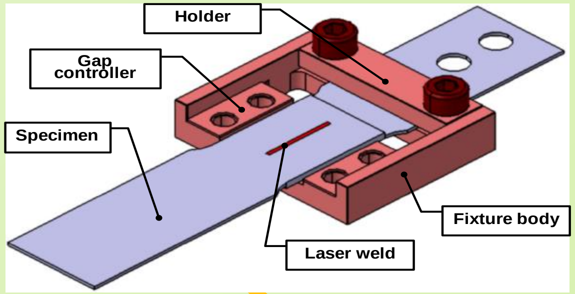
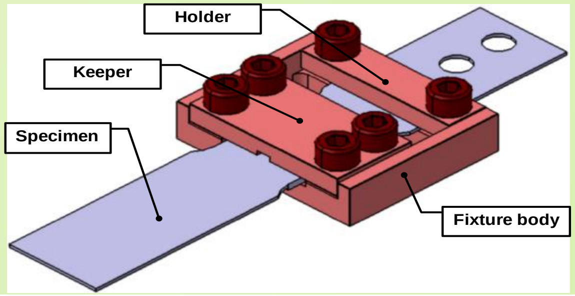
Testing fixture for pure-shear loading condition

- **Pure-shear failure test system for two-layered welded specimen**
  - **Conventional method for a pure-shear test: three-layered welding**
    - ✓ **Welding condition of the three-layered lap joint is different from the two-layered one → Need for a new jig system with the two-layered one**
  - **The main purpose of the jig system is to prevent rotation of the bead and to concentrate the plastic deformation around the bead**







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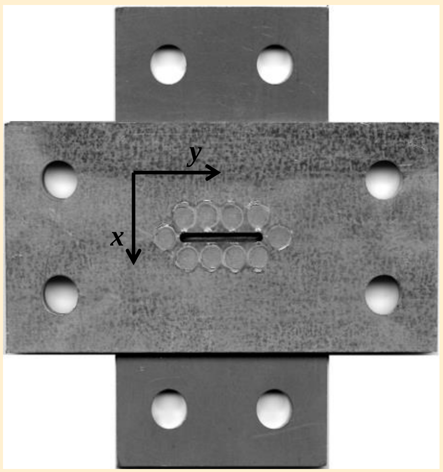
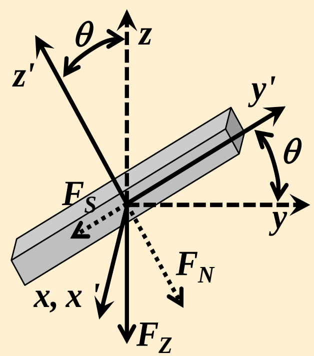
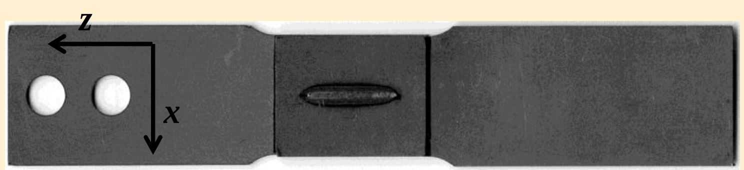
Testing fixtures and specimens

Specimen shape



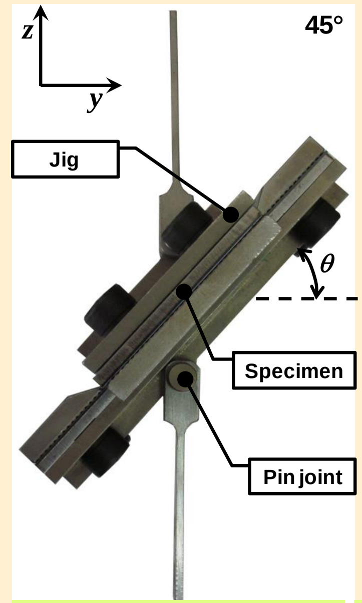


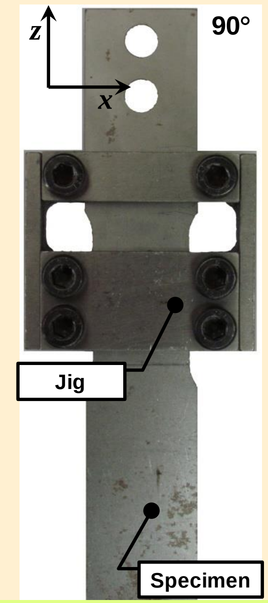
Specimen for normal and shear loading condition



Specimen for pure-shear loading condition

Testing fixtures





Fixture for normal and shear loading condition

Fixture for pure-shear loading condition

- Normal and shear loading condition: 0°, 15°, 30°, 45°, 60°, 75°, 80°, 85°
- Pure-shear loading condition: 90°

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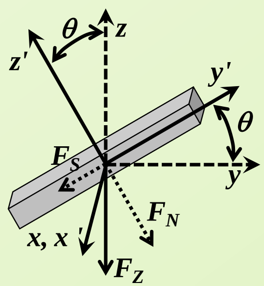
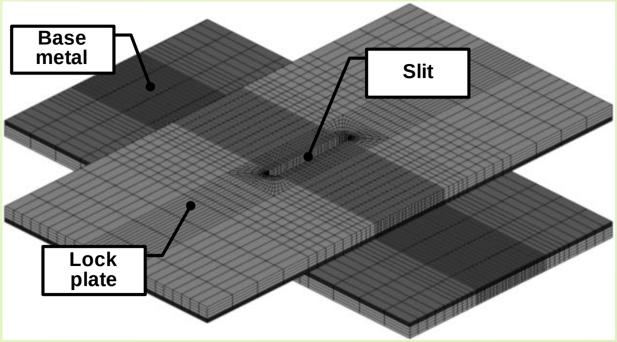
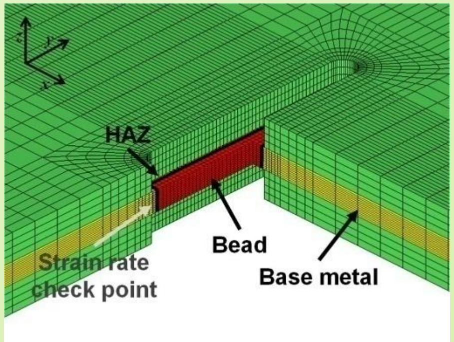
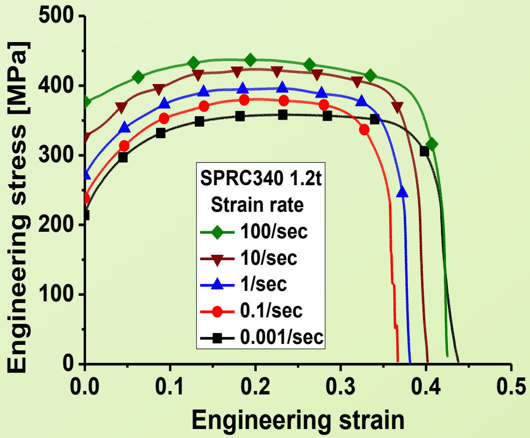
Determination of loading speed

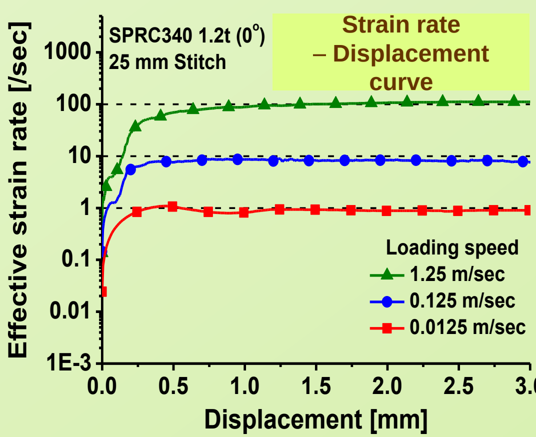
- **FE analysis of a laser-welded specimen under dynamic loading**
  - **Measuring point: crack initiation region of base metal around a bead**
  - **Target strain rate: 1/sec, 10/sec, 100/sec**
  - **Imposed loading speed: 0.0125 m/sec, 0.125 m/sec, 1.25 m/sec**

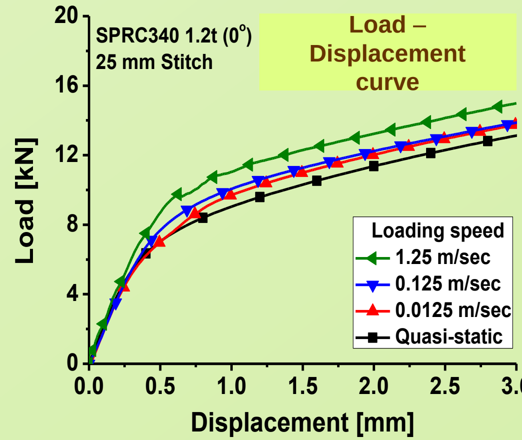












Dynamic failure tests of laser welds

Experimental conditions (1/2)

- **Dynamic failure test conditions**
  - **Laser welding condition**
    - ✓ **Set-up welding parameters as full penetration condition**

Material	Laser source	Laser power [kW]	Welding speed [m/min]	Focal length [mm]	Focus
SPRC340 1.2t	Fiber laser	4.00	3.00	450	On the base metal surface

Type	Testing Machine	Strain rate [/sec]	Crosshead speed [m/sec]	Loading angle [°]
Quasi-static	INSTRON 5583	0.004	5×10^{-5}	0° 15° 30° 45° 60° 75° 80° 85° 90°
Dynamic	High Speed Material Testing Machine (HSMTM)	1	0.0125	
		10	0.125	
		100	1.25	

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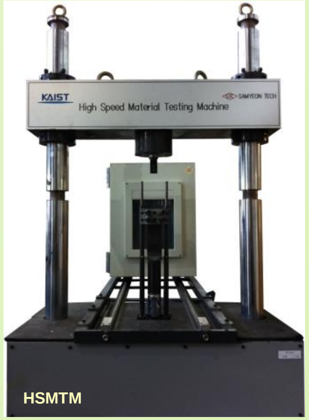
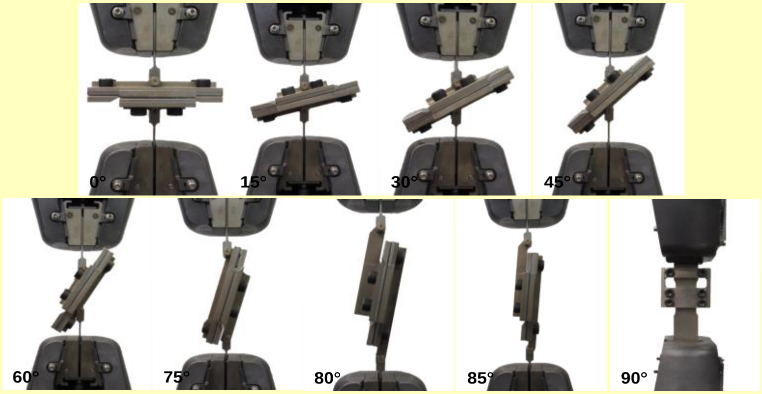
Experimental conditions (2/2)

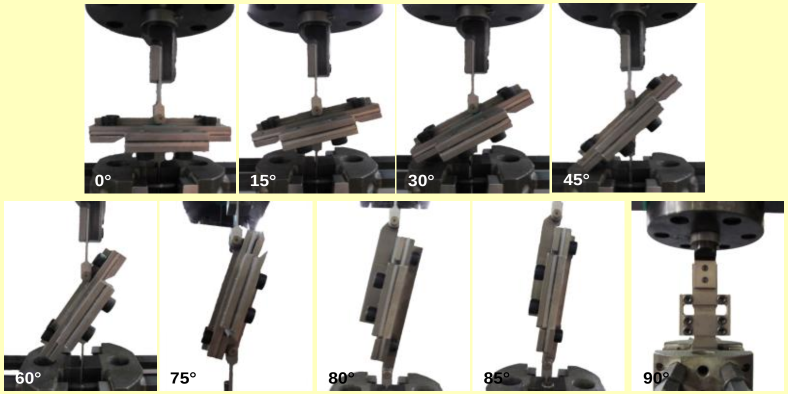
- **Quasi-static loading condition**
  - Apparatus: INSTRON 5583
  - Loading speed: 5×10^{-5} m/sec
  - Strain rate: 0.004/sec
- **Dynamic loading condition**
  - Apparatus: HSMTM
  - Loading speed: 0.0125 m/sec, 0.125 m/sec, 1.25 m/sec
  - Strain rate: 1/sec, 10/sec, 100/sec



Quasi-static

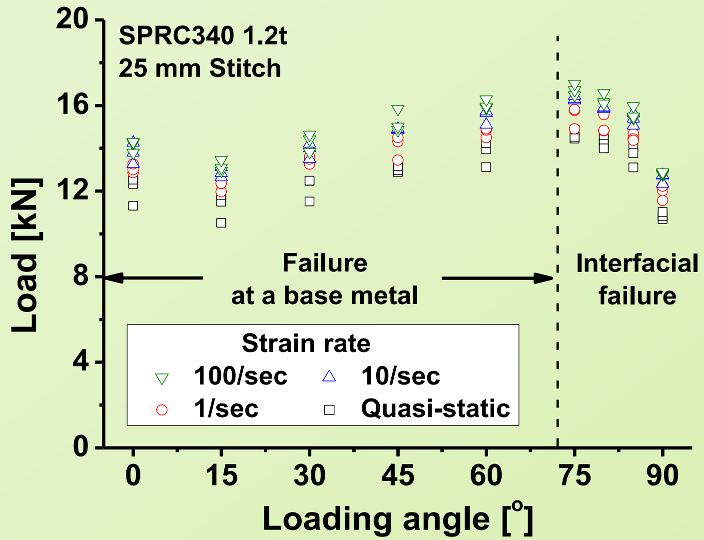


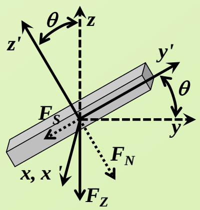
Dynamic



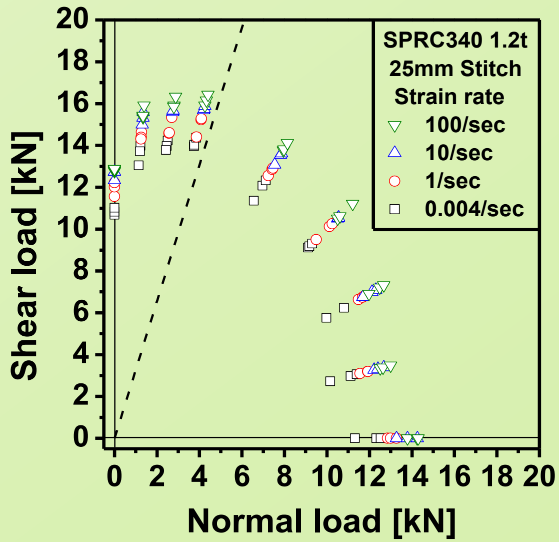
Experimental results

- **Failure loads and failure contour w.r.t. strain rate**
  - **Failure characteristics of laser welds w.r.t. loading angle**
    - ✓ **0°~15° : failure load decreases with an increase in the loading angle**
    - ✓ **15°~75°: failure load increases with an increase in the loading angle**
    - ✓ **75°~90°: failure load decreases with an increase in the loading angle because of failure mode change from a base metal failure to an interfacial failure**
      -- weak to the shear load acting on the neutral surface of a bead
  - **Failure loads of laser welds increase with an increase of a strain rate**
    → Failure loads of laser welds are dependent on the strain rate



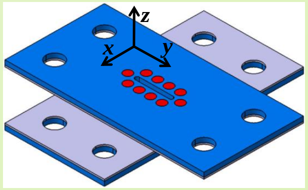


$$F_N = F_Z \cos\theta$$
$$F_S = F_Z \sin\theta$$



Review of the failure characteristics of laser welds

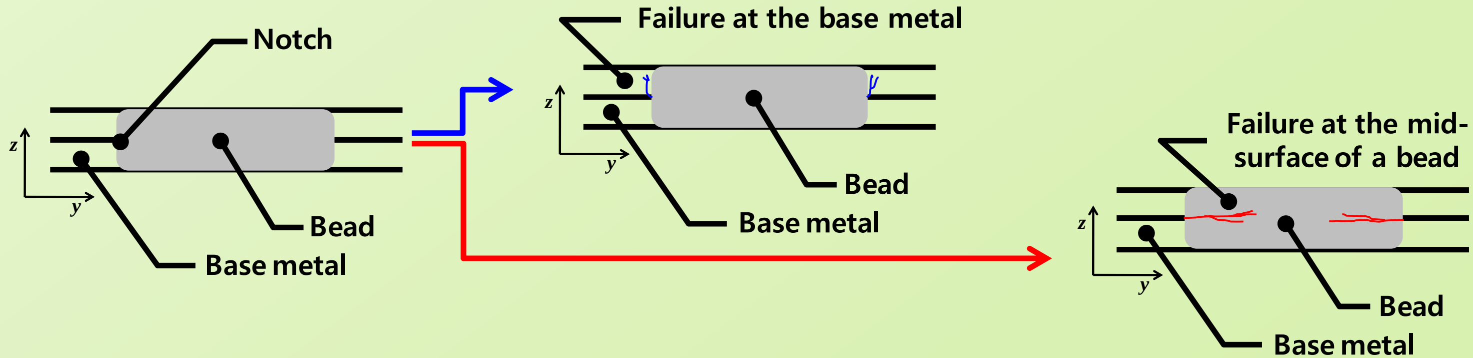
- **Review of the change in the failure mode from a base metal failure to an interfacial failure**



1. Stress concentration at the end of a bead by an external load
2. Crack is initiated at the base metal or the bead
   - ✓ Loading angle of 0° to 60°: crack is initiated at the base metal
   - ✓ Loading angle of 75° to 90°: crack is initiated at the bead

3-1. Base metal failure
   - ✓ Base metal torn by the propagation of the crack in the thickness direction

3-2. Interfacial failure
   - ✓ The initial crack propagated in the shear load dominant direction
   - ✓ The bead is more brittle than the base metal after laser welding processes

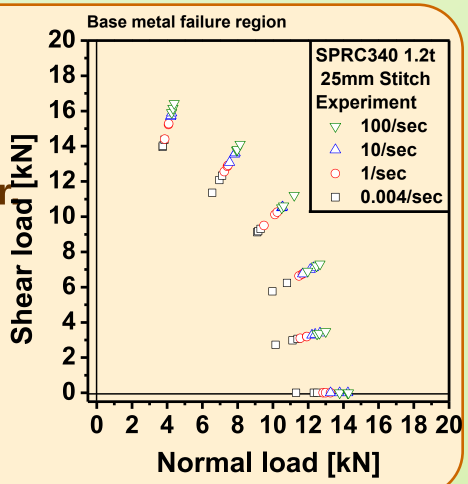


New dynamic failure criterion of laser welds

Characteristics of the failure contour

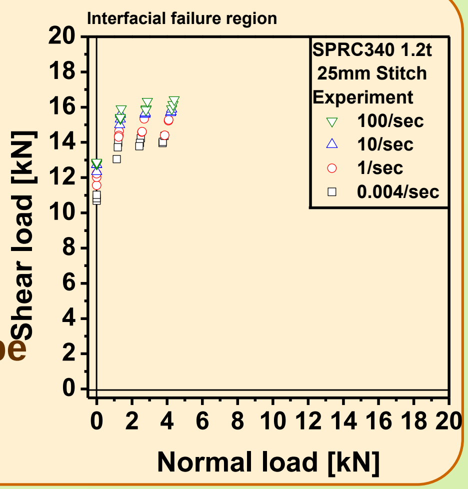
Base metal failure region

- The shear failure load increases as the normal failure load decrease with increase of the loading angle.
- The base metal failure contour shows a near-elliptical contour.
- Failure contour is extended with an increase of strain rate.
- In the case of the base metal failure region, the failure of laser welds can be predicted by β-norm function.



Interfacial failure region

- The shear failure load decreases as the normal failure load decrease with increase of the loading angle.
- Failure contour is extended with an increase of strain rate.
- In the case of the interfacial failure region, it is impossible to predict the failure of laser welds by β-norm function.
- Consequently, a new criterion has to be introduced to describe the interfacial failure other than the failure criterion for the base metal failure.



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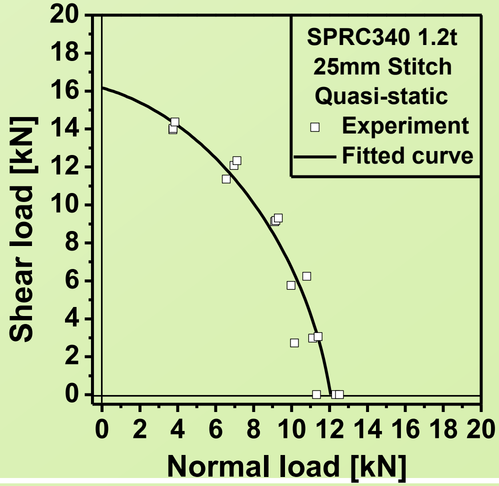
Base metal failure criterion

- **Proposal of a base metal failure criterion**
  - **Base metal failure criterion with a shape of β-norm function**
    - ✓ **The shear failure load increases as the normal failure load decrease with increase of the loading angle.**
    - ✓ **The base metal failure contour shows a near-elliptical contour.**
      $\rightarrow$ Approximation of the failure contour with β-norm function
    - ✓ **Determination of constants**
      - Normal failure load (F_N) is obtained from experimental results
      - Virtual shear failure load ($\bar{F}_S$) is obtained from interpolation results
      - Shape parameter(β) is obtained from interpolation results

$$\left(\frac{f_n}{F_N}\right)^2 + \beta\left(\frac{f_n}{F_N}\right)\left(\frac{f_s}{\bar{F}_S}\right) + \left(\frac{f_s}{\bar{F}_S}\right)^2 = 1$$

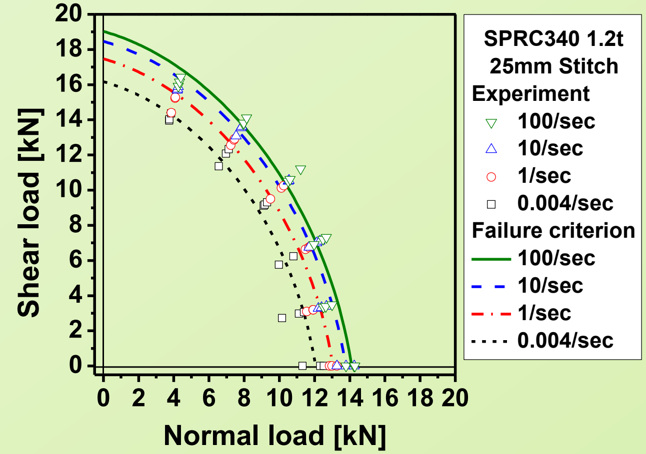
F_N : Normal failure load

$\bar{F}_S$: Virtual shear failure load



Strain effect of the base metal failure region

- **Dynamic failure criterion for the base metal failure region**
  - Failure contour takes similar shapes with various strain rate $\rightarrow \beta$ can be regarded as independent of the strain rate
  - Exponential function of the logarithm of the strain rate provides an accurate description for the strain-rate sensitivity of the normal and virtual shear failure loads obtained from dynamic failure tests



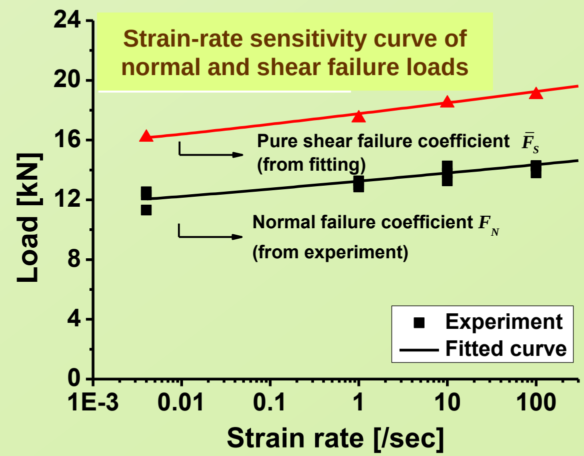
Dynamic failure criterion for the base metal failure region

$$\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)^2+\beta\left(\frac{f_n}{F_N(\dot{\varepsilon})}\right)\left(\frac{f_s}{\bar{F}_S(\dot{\varepsilon})}\right)+\left(\frac{f_s}{\bar{F}_S(\dot{\varepsilon})}\right)^2=1$$

$$F_N=F_{N_0}\left(1+C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)^p\right)$$

$$\bar{F}_S=\bar{F}_{S_0}\left(1+C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)^p\right)$$

where,
- F_{N_0} : Quasi – static normal failure load
- $\bar{F}_{S_0}$: Quasi – static virtual shear failure load
- β : Failure parameter
- C, p : Strain – rate sensitivity parameter
- $\dot{\varepsilon}_{ref}$: reference strain rate (quasi-static)



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Interfacial failure criterion

- **Proposal of an interfacial failure criterion**
  - **Interfacial failure criterion is described empirically**
    - ✓ **The shear failure load decreases as the normal failure load decrease with increase of the loading angle. → Shear failure load increases non-linearly with increase of the normal failure load**
    - ✓ **Interfacial failure criterion is represented in a form of a modified power law**
    - ✓ F_S^* **is the corresponding shear failure load for the normal load fn acting on laser welds in the interfacial failure region.**
    - ✓ **Interfacial failure takes place when the ratio of the shear failure load** F_S^* **to the shear load f_s acting on a laser weld reaches to 1**

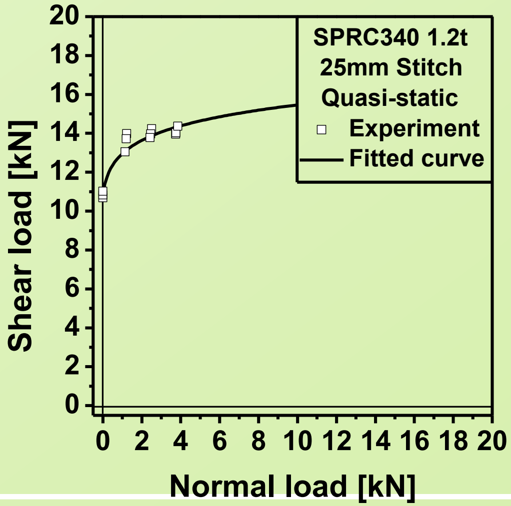
$$\frac{f_s}{F_S^*\left(f_n\right)} = 1$$

$$F_S^*\left(f_n\right) = K\left(a + f_n\right)^n$$

where K: load coefficient

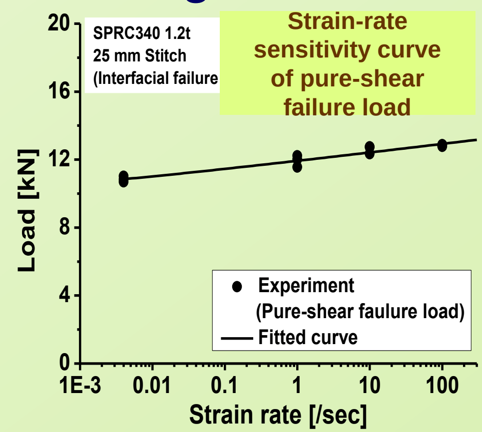
a: additive normal load

n: load-hardening exponent



Strain effect of the interfacial failure region

- **Dynamic failure criterion for the interfacial failure region**
  - **Strain rate effect to the shear failure loads**
    - ✓ **Strain rate effect to the shear failure loads is expressed by the exponential function for the logarithm of strain rate***
  - **Representation of change of shear failure load increases w.r.t. normal failure loads at each strain rate****



Dynamic failure criterion for the interfacial failure region

$$\frac{f_s}{F_S^*(f_n,\dot{\varepsilon})}=1$$

$$F_S^*(f_n,\dot{\varepsilon})=K\left[a+\left(1-\frac{\ln\dot{\varepsilon}^*}{\ln 10^9}\right)^m f_n\right]^n\left[1+D\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^q\right]$$

Shear failure load increases w.r.t. normal failure loads in first bracket is described by function of normal failure loads and strain rate

Strain rate hardening term of shear failure loads w.r.t normal failure loads

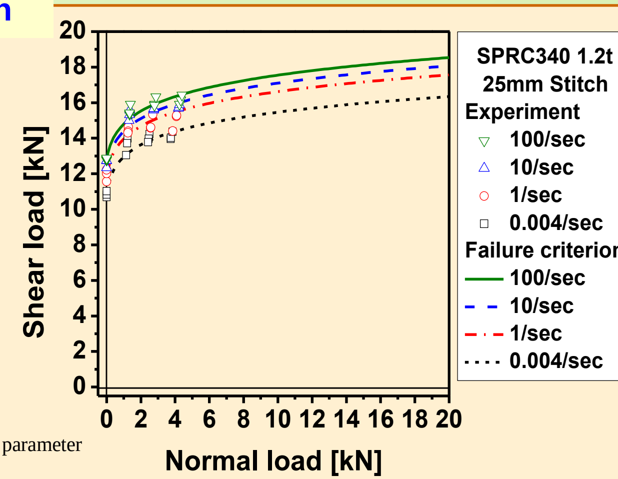
where $\dot{\varepsilon}^*=\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$, $\dot{\varepsilon}_0=0.004/\text{sec}$

K: load coefficient

a: additive normal load

n: load-hardening exponent

D,q,m: Strain – rate sensitivity parameter



*Ref.) W. J. Kang, S. S. Cho, H. Huh and D. T. Chung, "Modified Johnson-Cook Model for Vehicle Body Crashworthiness Simulation", Int. J. Vehicle Des. 21 424-435, 1999.

**Ref.) A. S. Khan and S. Huang, "Experimental and Theoretical Study of Mechanical Behavior of 1100 Aluminum in the Strain Rate Range 10^{-5}-$10^{4}s^{-1}$", Int. J. Plasticity 8 397-424, 1992.

Dynamic failure criterion for laser welds

Dynamic failure model

$$\text{max. } \varphi\left(\phi_b\left(f_n, f_s, \dot{\varepsilon}\right), \phi_i\left(f_n, f_s, \dot{\varepsilon}\right)\right) = 1$$

1. Base metal failure model

$$\phi_b\left(f_n, f_s, \dot{\varepsilon}\right) = \left(\frac{f_n}{F_N\left(\dot{\varepsilon}\right)}\right)^2 + \beta\left(\frac{f_n}{F_N\left(\dot{\varepsilon}\right)}\right)\left(\frac{f_s}{\bar{F}_S\left(\dot{\varepsilon}\right)}\right) + \left(\frac{f_s}{\bar{F}_S\left(\dot{\varepsilon}\right)}\right)^2$$

$$F_N = F_{N_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)^p\right)$$

$$\bar{F}_S = \bar{F}_{S_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)^p\right)$$

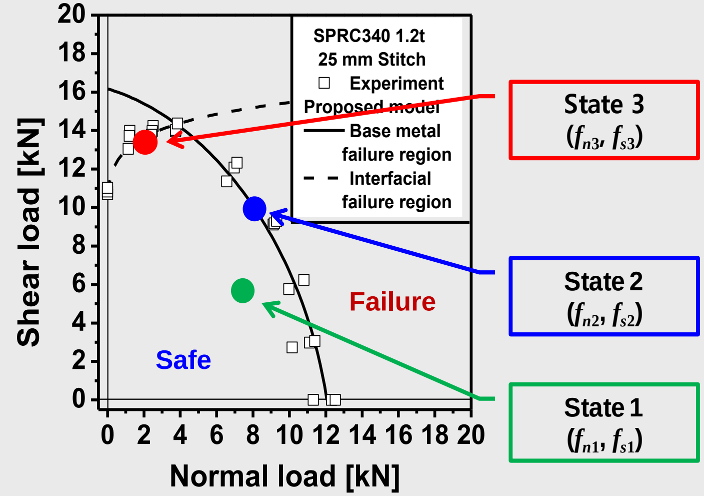
2. Interfacial failure criterion

$$\phi_i\left(f_n, f_s, \dot{\varepsilon}\right) = \frac{f_s}{F_s^*\left(f_n, \dot{\varepsilon}\right)}$$

$$F_s^*\left(f_n, \dot{\varepsilon}\right) = K\left[a + \left(1 - \frac{\ln\dot{\varepsilon}^*}{\ln 10^9}\right)^m f_n\right]^n \left[1 + D\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^q\right]$$

where $\dot{\varepsilon}^* = \dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$, $\dot{\varepsilon}_0 = 0.004/\text{sec}$

Application example



1. State 1 (f_{n1}, f_{s1})
   I. ϕ_b<1 and ϕ_i<1
   II. Safe
2. State 2 (f_{n2}, f_{s2})
   I. ϕ_b=1 and ϕ_i<1
   II. Base metal failure
3. State 3 (f_{n3}, f_{s3})
   I. ϕ_b<1 and ϕ_i=1
   II. Interfacial failure

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Interpolation of a failure contour with a newly proposed dynamic failure criterion

- **Stitch-type laser weld of 25 mm on SPRC340 1.2t**

$$\max.\ \varphi\left(\phi_b\left(f_n, f_s, \dot{\varepsilon}\right), \phi_i\left(f_n, f_s, \dot{\varepsilon}\right)\right) = 1$$

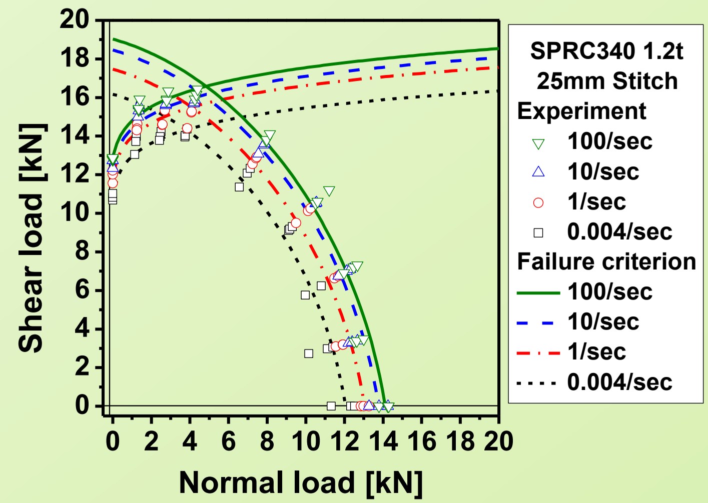
$$\phi_b\left(f_n, f_s, \dot{\varepsilon}\right) = \left(\frac{f_n}{F_N\left(\dot{\varepsilon}\right)}\right)^2 + 0.41\left(\frac{f_n}{F_N\left(\dot{\varepsilon}\right)}\right)\left(\frac{f_s}{\bar{F}_S\left(\dot{\varepsilon}\right)}\right) + \left(\frac{f_s}{\bar{F}_S\left(\dot{\varepsilon}\right)}\right)^2$$

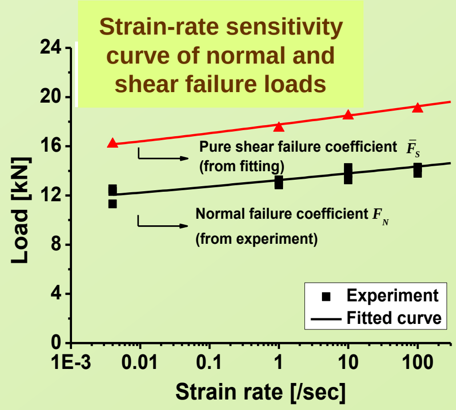
$$F_N\left(\dot{\varepsilon}\right) = 12.06\left[1 + 0.01563\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)^{1.07976}\right]$$

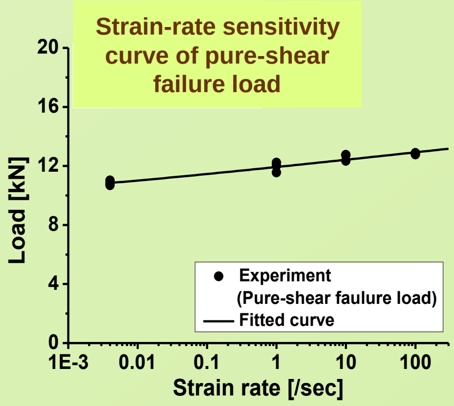
$$\bar{F}_S\left(\dot{\varepsilon}\right) = 16.17\left[1 + 0.01563\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)^{1.07976}\right]$$

$$\phi_i\left(f_n, f_s, \dot{\varepsilon}\right) = \frac{f_s}{F_s^*\left(f_n, \dot{\varepsilon}\right)}$$

$$F_s^*\left(f_n, \dot{\varepsilon}\right) = 12.83\left[0.12487 + \left(1 - \frac{\ln\dot{\varepsilon}^*}{\ln 10^9}\right)^{0.89909} f_n\right]^{0.08045} \times\left[1 + 0.01563\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{1.07976}\right]$$







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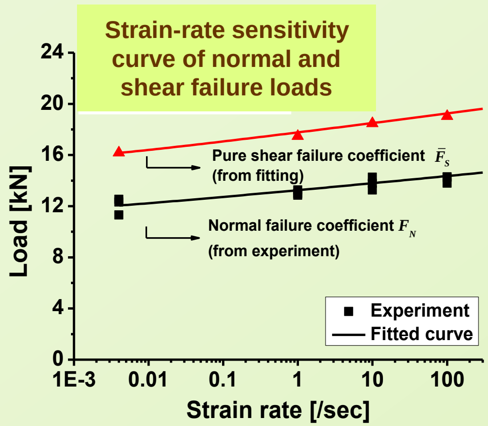
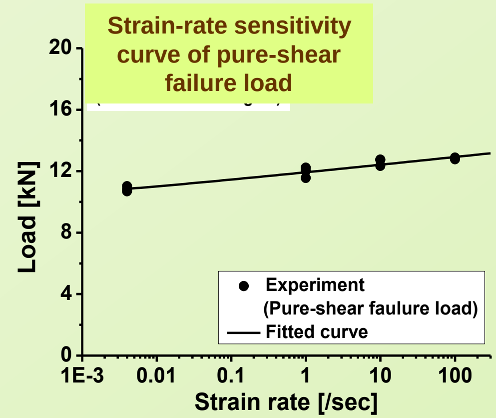
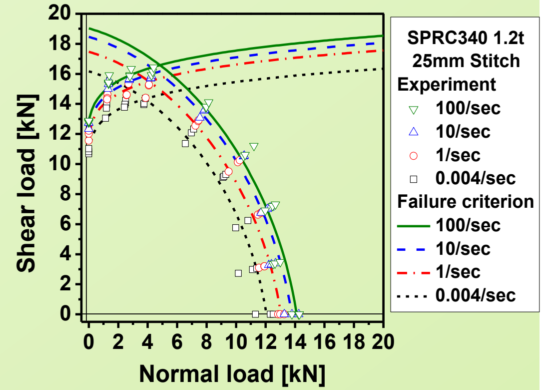
Interpolation of a failure contour with a newly proposed dynamic failure criterion

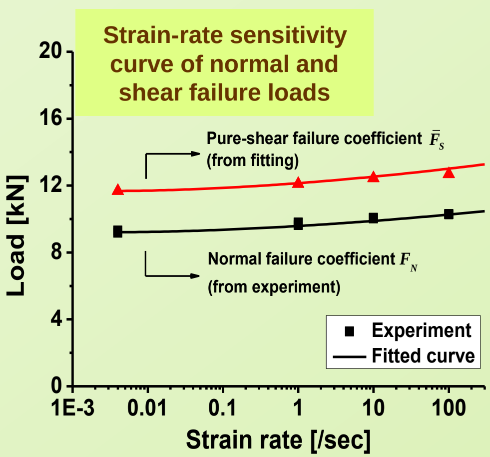
Stitch-type laser weld of 25 mm on SPRC340 1.2t

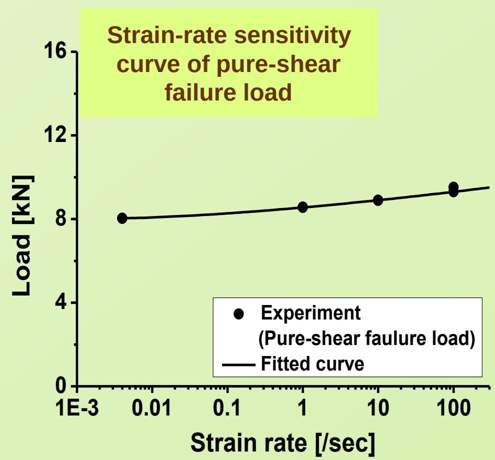


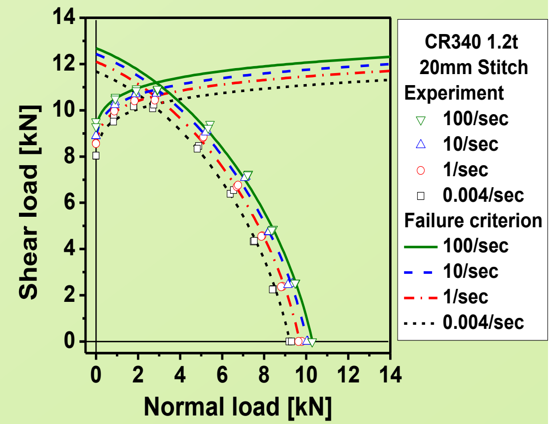




Stitch-type laser weld of 20 mm on CR340 1.2t







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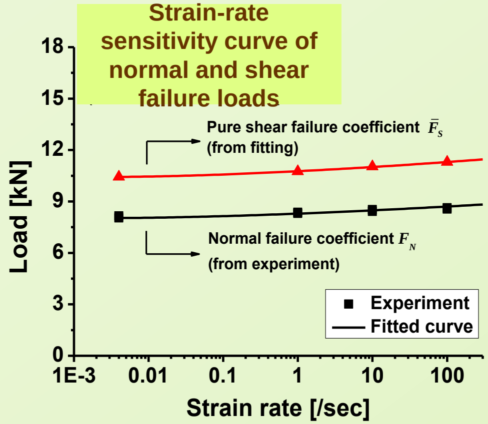
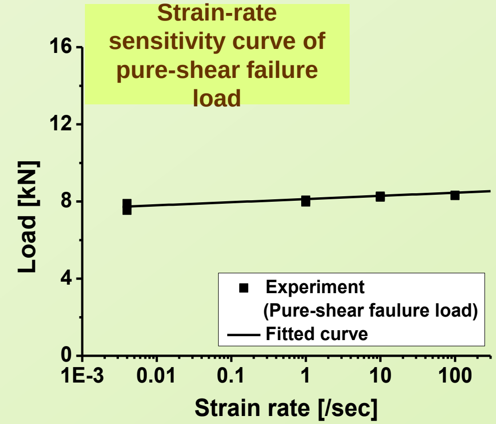
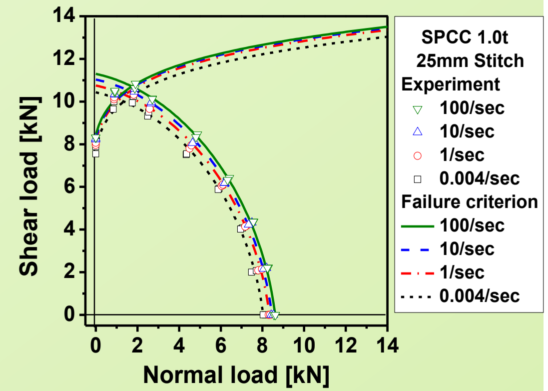
Interpolation of a failure contour with a newly proposed dynamic failure criterion

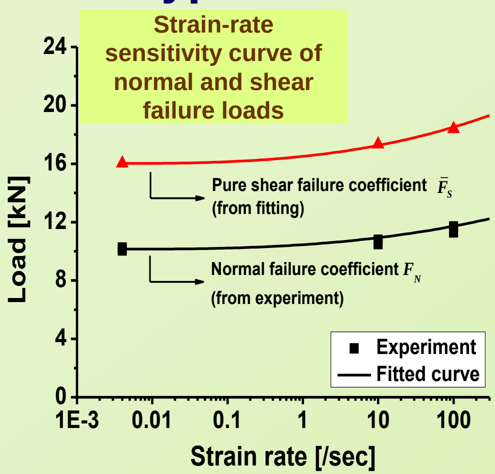
Stitch-type laser weld of 25 mm on SPCC 1.0t

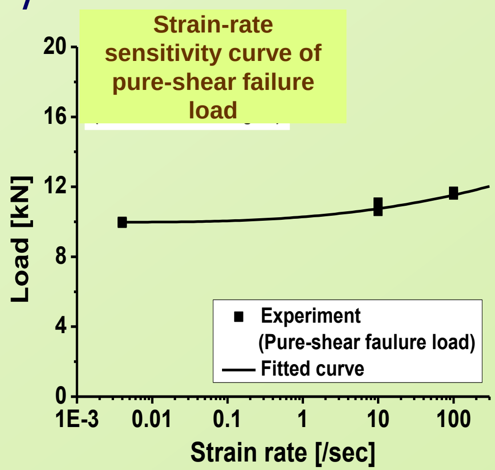


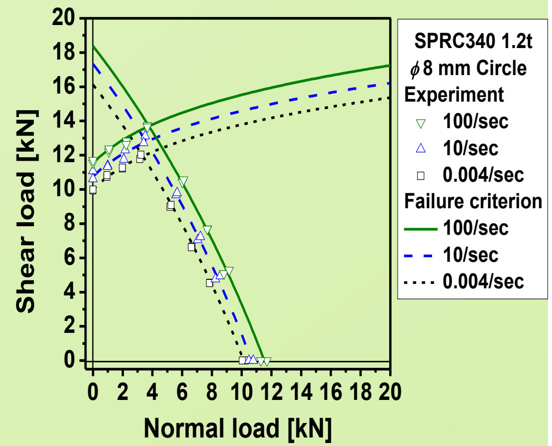




O-type laser weld of ϕ8 mm on SPRC340 1.2t







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Interpolation of a failure contour with a newly proposed dynamic failure criterion

Coefficients of the dynamic failure model of laser welds

$$\max.\ \varphi\left(\phi_b\left(f_n, f_s, \dot{\varepsilon}\right), \phi_i\left(f_n, f_s, \dot{\varepsilon}\right)\right) = 1$$

1. Base metal failure model

$$\phi_b\left(f_n, f_s, \dot{\varepsilon}\right) = \left(\frac{f_n}{F_N\left(\dot{\varepsilon}\right)}\right)^2 + \beta\left(\frac{f_n}{F_N\left(\dot{\varepsilon}\right)}\right)\left(\frac{f_s}{\bar{F}_S\left(\dot{\varepsilon}\right)}\right) + \left(\frac{f_s}{\bar{F}_S\left(\dot{\varepsilon}\right)}\right)^2$$

$$F_N = F_{N_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)^p\right)$$

$$\bar{F}_S = \bar{F}_{S_0}\left(1 + C\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)^p\right)$$

2. Interfacial failure criterion

$$\phi_i\left(f_n, f_s, \dot{\varepsilon}\right) = \frac{f_s}{F_s^*\left(f_n, \dot{\varepsilon}\right)}$$

$$F_s^*\left(f_n, \dot{\varepsilon}\right) = K\left[a + \left(1 - \frac{\ln\dot{\varepsilon}^*}{\ln 10^9}\right)^m f_n\right]^n\left[1 + D\left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^q\right]$$

where $\dot{\varepsilon}^* = \dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_0}$, $\dot{\varepsilon}_0 = 0.004/\text{sec}$

Material & Bead type	Base metal failure region					Interfacial failure region						Adjusted R^2
	F_{N0} [kN]	$\bar{F}_{S0}$ [kN]	β	C	p	K [kN]	a	m	n	D	q	
SPRC340 1.2t 25 mm stitch	12.06	16.17	0.41	0.01563	1.07976	12.83	0.12487	0.89909	0.08045	0.01563	1.07976	0.9377
CR340 1.2t 20 mm stitch	9.21	11.68	0.59	0.00209	1.72755	9.61	0.05514	1.49061	0.06167	0.00512	1.47840	0.9838
SPCC 1.0t 25mm stitch	8.04	10.43	0.33	0.00210	1.58865	9.53	0.17328	0.68228	0.11836	0.00851	1.03035	0.9754
SPRC340 1.2t ϕ 8 mm circle	10.15	16.02	1.39	0.00030	2.70451	8.92	1.89786	0.26455	0.17625	0.00030	2.70451	0.9767

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Summary

Summary

- **Dynamic failure tests of laser welds under combined loading condition**
  - **Acquisition of the failure loads and the failure contours of laser welds w.r.t. strain rate**
  - **The transition point is observed around a loading angle of 75° due to the change in the failure mode from base metal failure to interfacial failure.**
- **Proposal of a new dynamic failure criterion for laser welds**
  - **The failure criteria are divided into two regions of base metal failure and interfacial failure.**
  - **The base metal failure region is expressed as a function of the normal and the virtual shear load, which is the so-called β-norm function while the interfacial failure region is represented in a form of a modified power law function.**
  - **Failure criteria are extended with an increase of strain rate.**

Conclusion

Conclusion

- Failure load of Spot weld and Laser weld under combined axial and shear load
  - Design the fixture and the specimen for failure tests of the weld under combined load conditions
  - Failure tests of the weld under combined axial and shear load
- Failure model of the Spot weld and Laser weld for the FE analysis
  - Suggest new engineering failure model of the spot weld
  - Suggest new engineering failure model of the laser weld
  - Provide relatively good description of the failure load of the spot weld
  - FE analyses of lap-shear tests demonstrate that proposed failure model is valid for applying the macroscopic FE analysis
  - Laser weld is weak under shear load compared to Spot weld

Thank You Very Much
for Your Kind Attention

Q & A

Related Papers

- J. H. Song, H. Huh, H. G. Kim and S. H. Park, Evaluation of the Finite Element Modeling of a Spot Welded Region for Crash Analysis, International Journal of Automotive Technology, Vol.7, No.3, pp.329~336 (2006)
- J. H. Song, H. Huh, J. H. Lim and S. H. Park, Effect of Tensile Speed on the Failure load of a Spot Weld under Combined Loading Conditions, International Journal of Modern Physics B, Vol.22, No.9-11, pp.1469~1474 (2008)
- J.-W. Ha, J. Song, H. Huh, J. H. Lim, S. Park, Dynamic material properties of the heat-affected zone (HAZ) in resistance spot welding, International Journal of Modern Physics B, Vol.22, No.31/32, pp.5800~5806 (2008)
- J. H. Song, H. Huh, Failure characterization of spot welds under combined axial-shear loading conditions, International Journal of Mechanical Sciences, Vol.53, pp.513-525(2011)
- J. Ha, H. Huh, Y.-D. An, C. Park, Compatible finite element modeling of laser welded region for crash analysis of autobody assemblies, Materials Research Innovations, Vol.15, No.1, pp.412-416(2011)
- J. Ha, H. Huh, J.-H. Song, J.-H. Lim, Prediction of Failure Characteristics of Spot Welds of DP and Trip Steels with an Equivalent Strength Failure Model, International Journal of Automotive Technology, Vol. 14, No. 1, pp. 67-78 (2013)
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- H. Huh, J. H. Song. H. J. Lee, Dynamic hardening equation of the auto-body steel sheet with the variation of temperature, Int. J. Automotive Technology, Vol. 13, No. 1, pp. 43−60 (2012)

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- J. H. Song, H. Huh, H. G. Kim and S. H. Park, Evaluation of the Finite Element Modeling of a Spot Welded Region for Crash Analysis, International Journal of Automotive Technology, Vol.7, No.3, pp.329~336 (2006)
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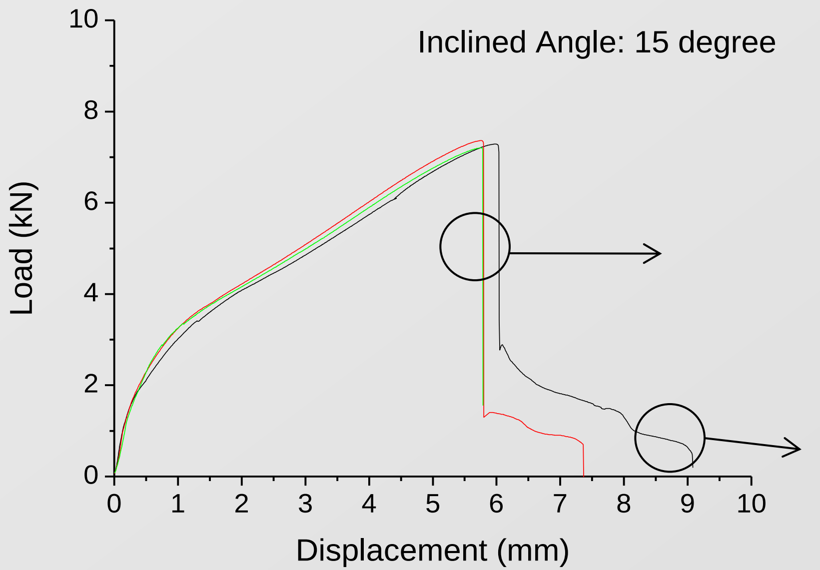
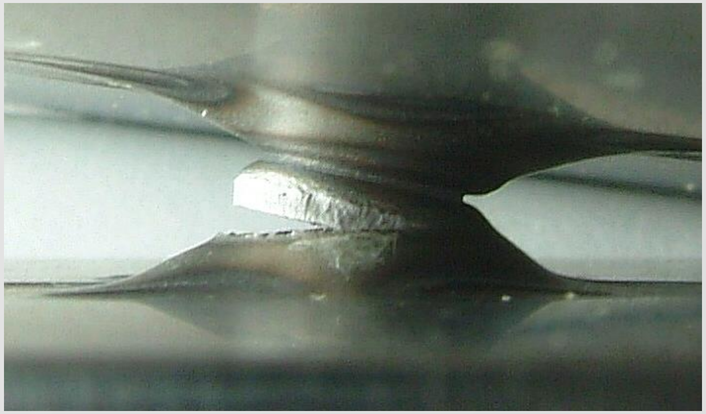
Failure Tests of the Spot Weld under Combined Load

- **Experimental Result**
  - **Inclined angle: 15˚**
    - ✓ **Load–Displacement curves**

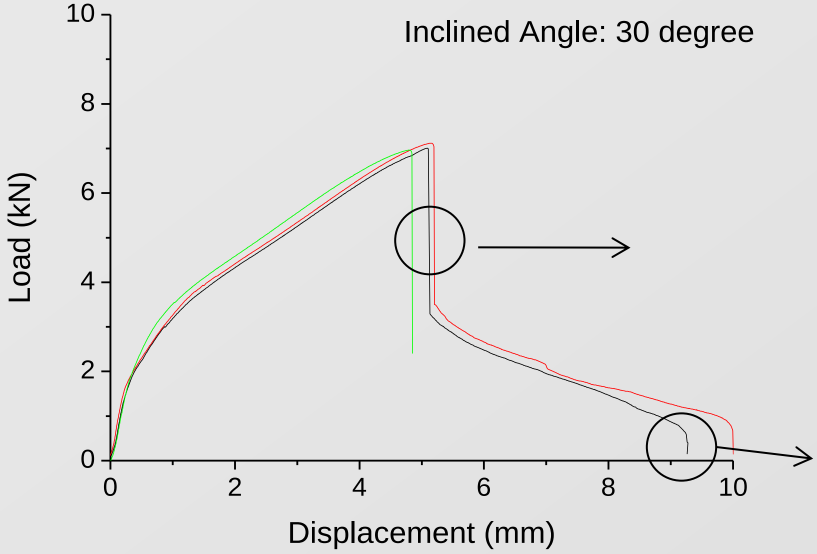


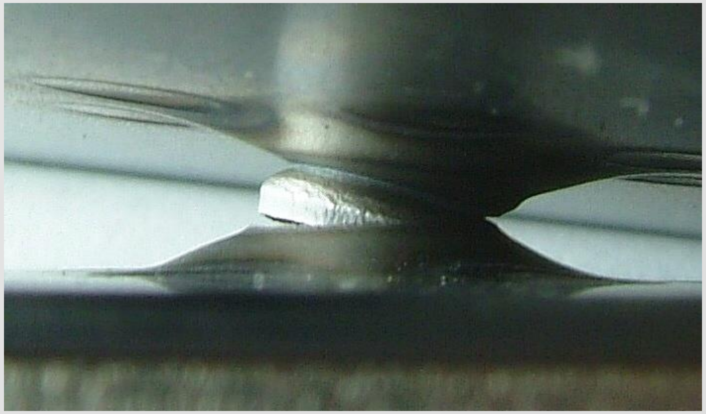


Specimen	1	2	3
Max. Load (kN)	7.286	7.361	7.204

Failure Tests of the Spot Weld under Combined Load

- **Experimental Result**
  - **Inclined angle: 30˚**
    - ✓ **Load–Displacement curves**

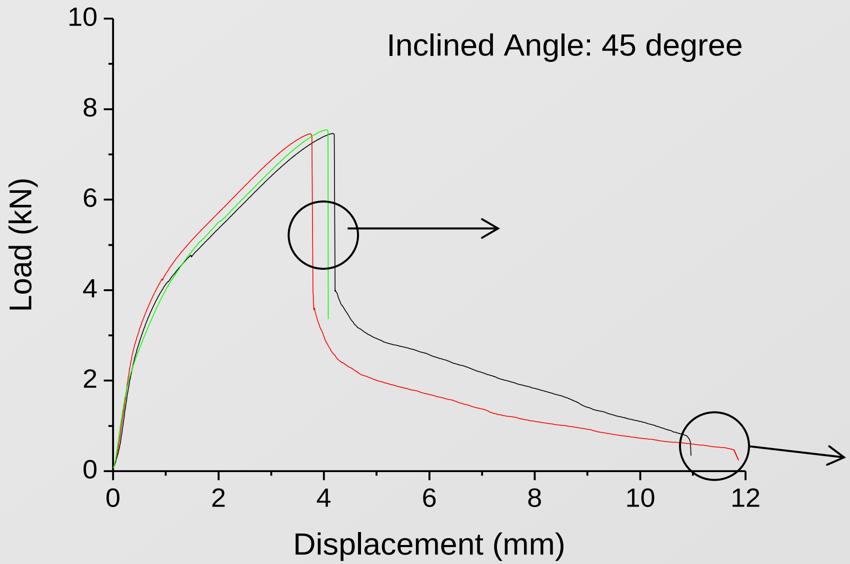


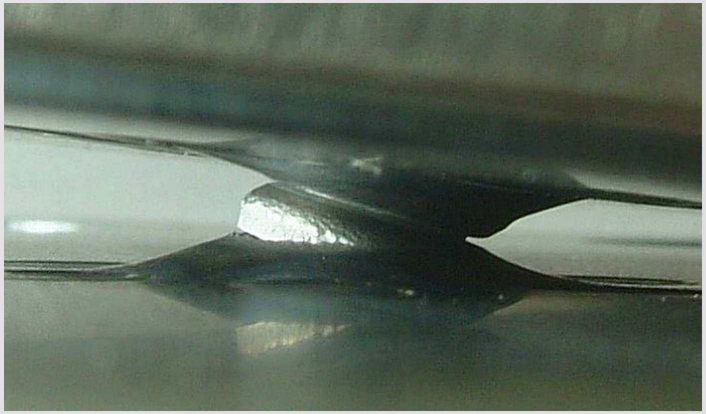


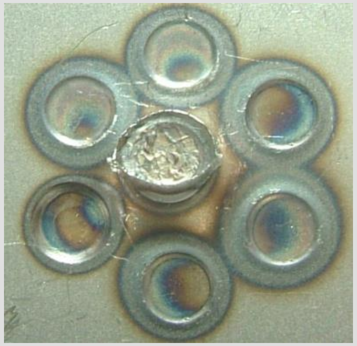
Specimen	1	2	3
Max. Load (kN)	7.134	7.219	7.113

Failure Tests of the Spot Weld under Combined Load

- **Experimental Result**
  - **Inclined angle: 45˚**
    - ✓ **Load–Displacement curves**



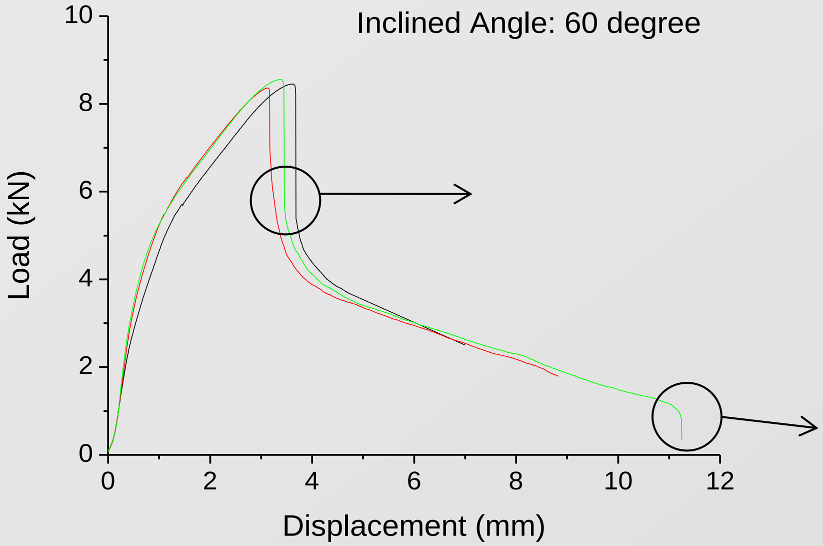


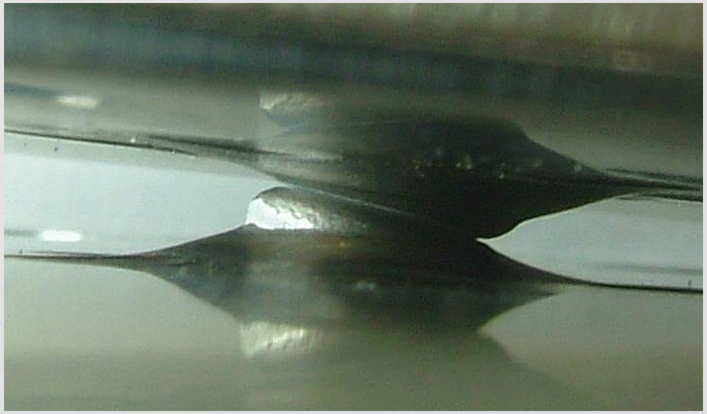


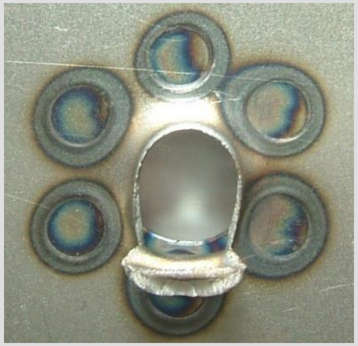
Specimen	1	2	3
Max. Load (kN)	7.462	7.453	7.542

Failure Tests of the Spot Weld under Combined Load

- **Experimental Result**
  - **Inclined angle: 60°**
    - ✓ **Load–Displacement curves**



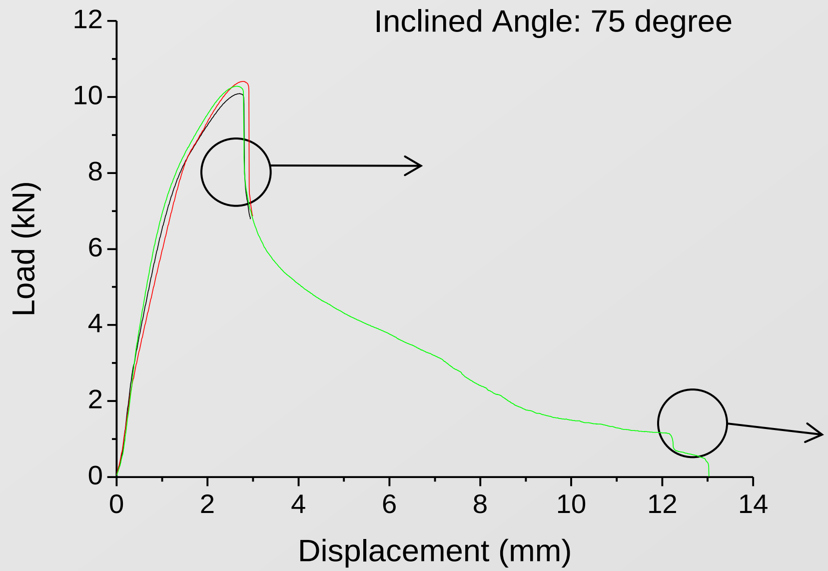


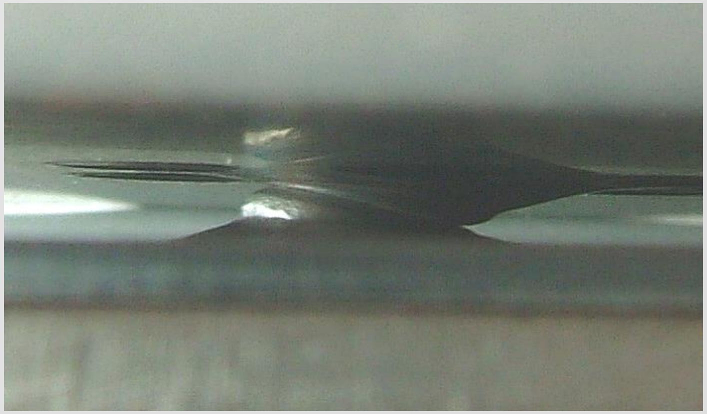


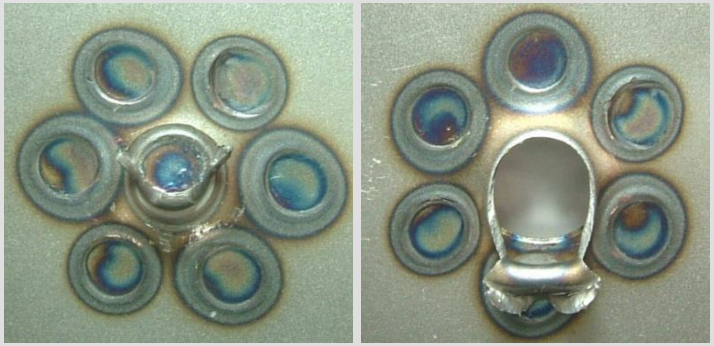
Specimen	1	2	3
Max. Load (kN)	8.448	8.364	8.553

Failure Tests of the Spot Weld under Combined Load

- **Experimental Result**
  - **Inclined angle: 75°**
    - ✓ **Load–Displacement curves**



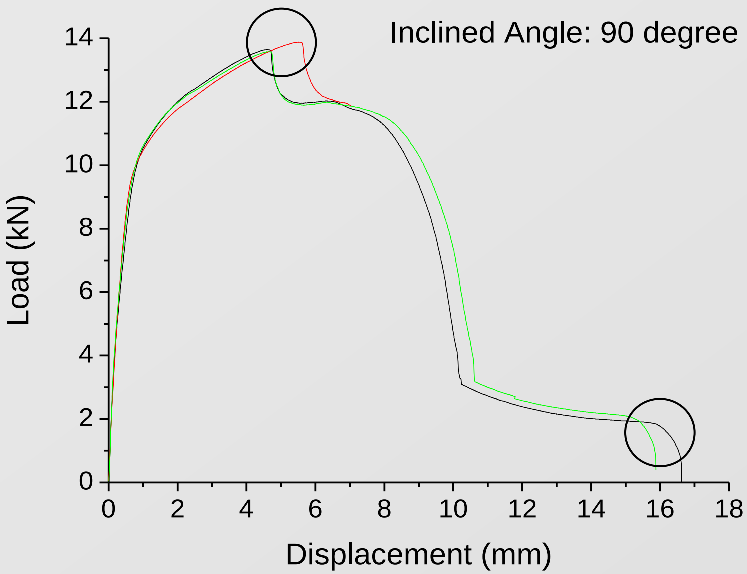




Specimen	1	2	3
Max. Load (kN)	10.21	10.09	10.41

Failure Tests of the Spot Weld under Combined Load

- **Experimental Result**
  - **Inclined angle: 90˚**
    - ✓ **Load–Displacement curves**



Specimen	**1**	**2**	**3**
Max. Load (kN)	13.35	13.48	13.57