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Effects of High Strain Rates on ASTM A992 and A572 Grade 50 Steel

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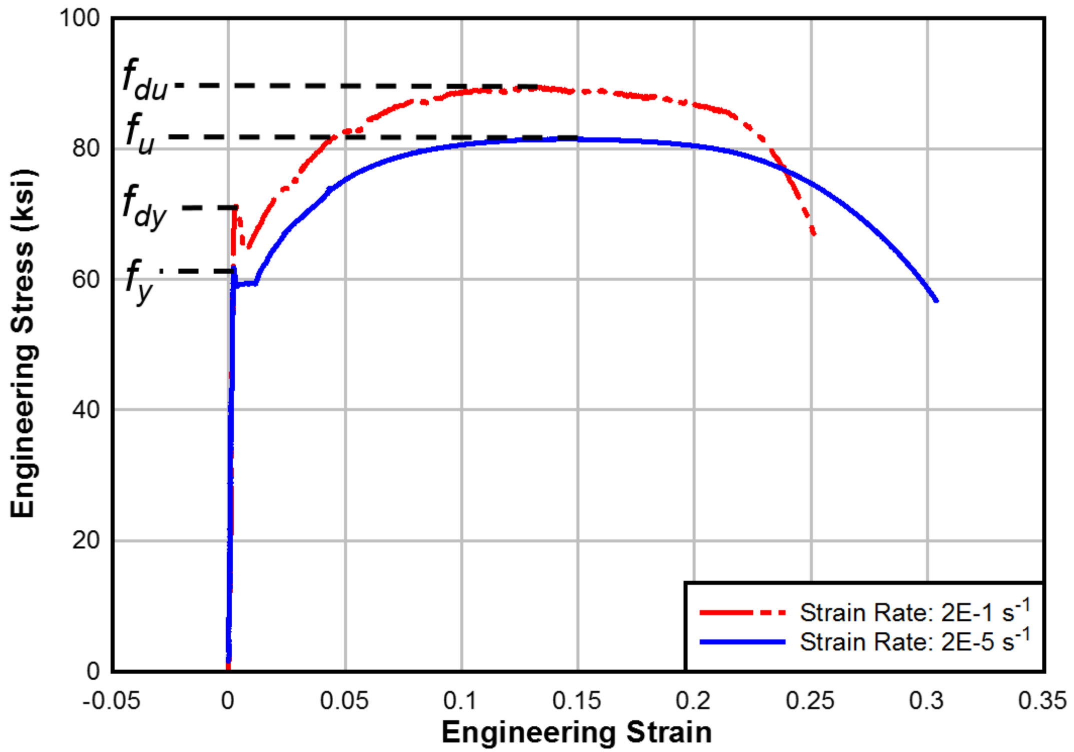
Dynamic Material Properties of Steel

Increased strain rate → Dynamic Increase Factor (DIF)

- Increased yield strength: DIF_y
- Increased ultimate tensile strength (UTS): DIF_u
- Unchanged modulus of elasticity
- Unchanged or slightly reduced elongation at rupture*



Experimental DIF:

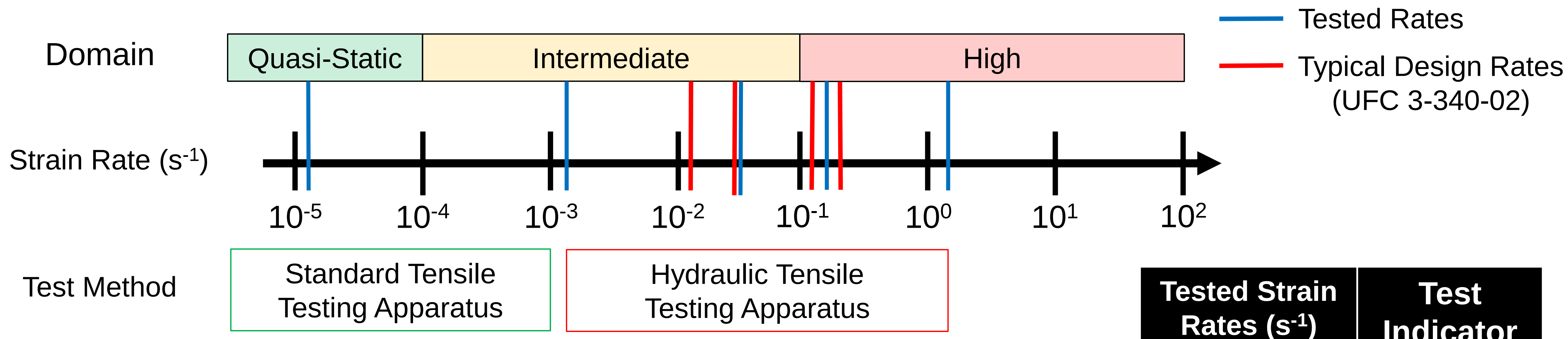
$$DIF_y = \frac{f_{dy}}{f_y}$$

$$DIF_u = \frac{f_{du}}{f_u}$$

f_{dy} = dynamic yield strength
f_{du} = dynamic UTS
f_y = static yield strength
f_u = static UTS

UFC 3-340-02: Structures to Resist the Effects of Accidental Explosions

Research Plan



Tested Strain Rates (s^{-1})	Test Indicator
0.00002	SR
0.002	DR1
0.05	DR2
0.2	DR3
2.0	DR4

Table 5-2 Dynamic Increase Factor, *DIF*, for Yield Stress of Structural Steels

Material	Bending		Tension or Compression	
	Low Pressure $(\dot{\varepsilon} = 0.10 \text{ in/in/sec})$	High Pressure $(\dot{\varepsilon} = 0.30)$	Low Pressure $(\dot{\varepsilon} = 0.02)$	High Pressure $(\dot{\varepsilon} = 0.05)$
A36	1.29	1.36	1.19	1.24
A588	1.19*	1.24*	1.12*	1.15*
A514	1.09	1.12	1.05	1.07

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Baseline Material Strength Properties (f_y & f_u)

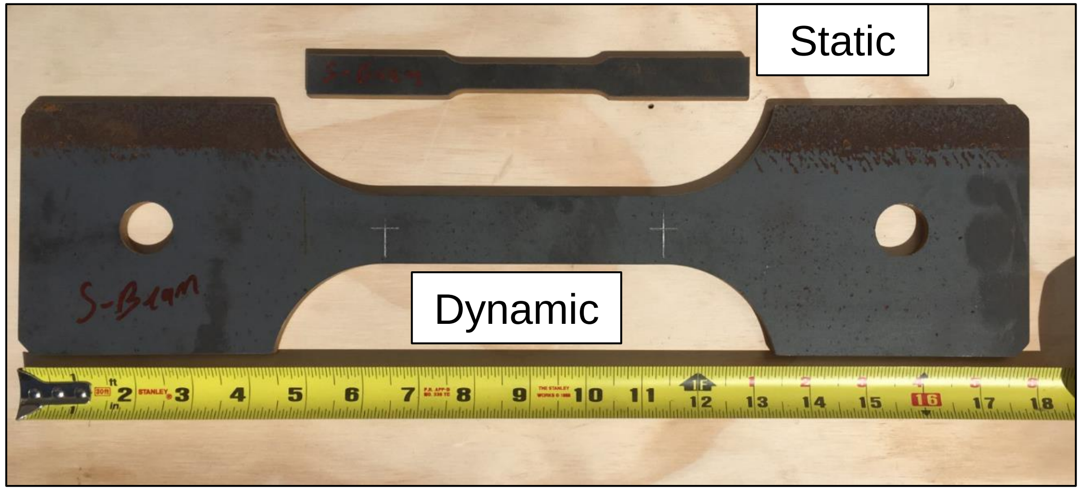
Instron 33R4206 Universal Testing System at ERDC-GSL

- Domestic A572-50 plate: 0.375 in. (9.525 mm) thick
- Domestic A992 S12x31.8 beam: 0.35-in.-web (8.89-mm) thickness
- ASTM E8 standard sheet-size specimen
- Static (quasi-static) strain rate of 0.00002 s^{-1}

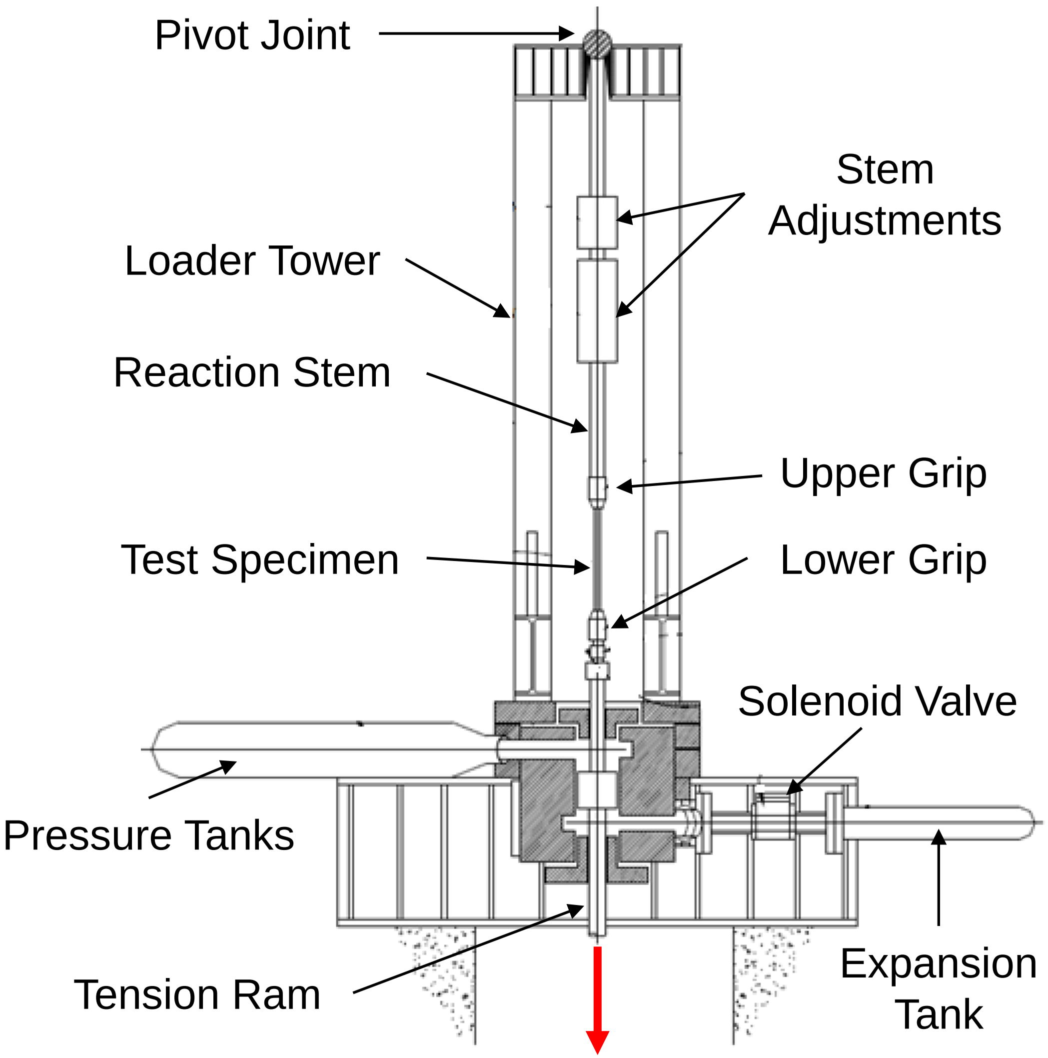
$$DIF_y = \frac{f_{dy}}{f_y}$$

$$DIF_u = \frac{f_{du}}{f_u}$$

Visual Comparison of Specimen Geometries



Dynamic Material Strength Properties (f_{dy} & f_{du})



ERDC-GSL's 200-kip-Capacity (890 kN) Hydraulic Loader

$$DIF_y = \frac{f_{dy}}{f_y}$$

$$DIF_u = \frac{f_{du}}{f_u}$$

Tested Strain Rates (s^{-1})	
0.00002	SR
0.002	DR1
0.05	DR2
0.2	DR3
2.0	DR4

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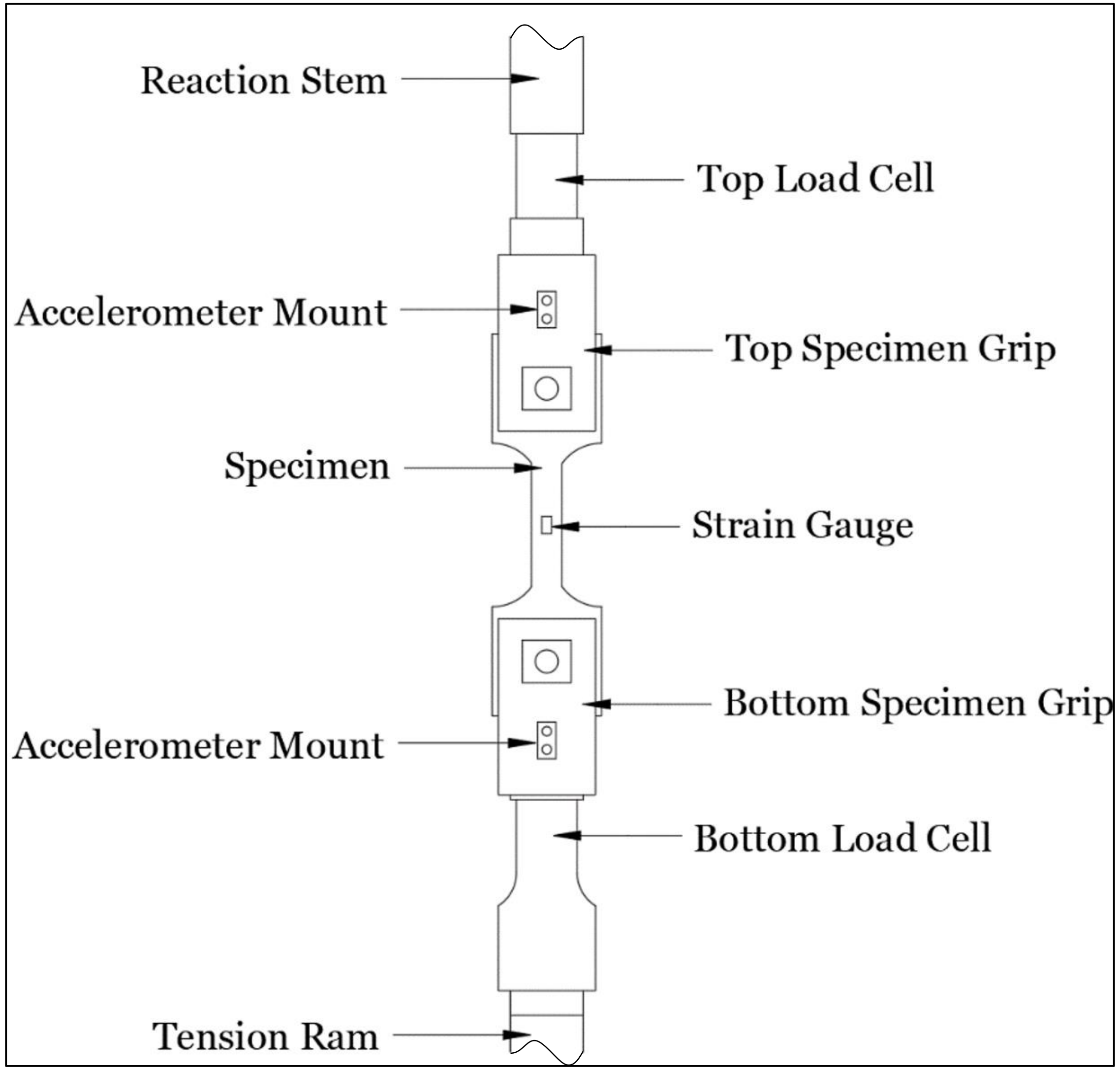
Instrumentation



- Stress calculated from top and bottom load cell data
- Inertial effects recorded by top and bottom accelerometers
- Elongation captured by high speed camera
- Strain gauge for calibration and highest strain rate

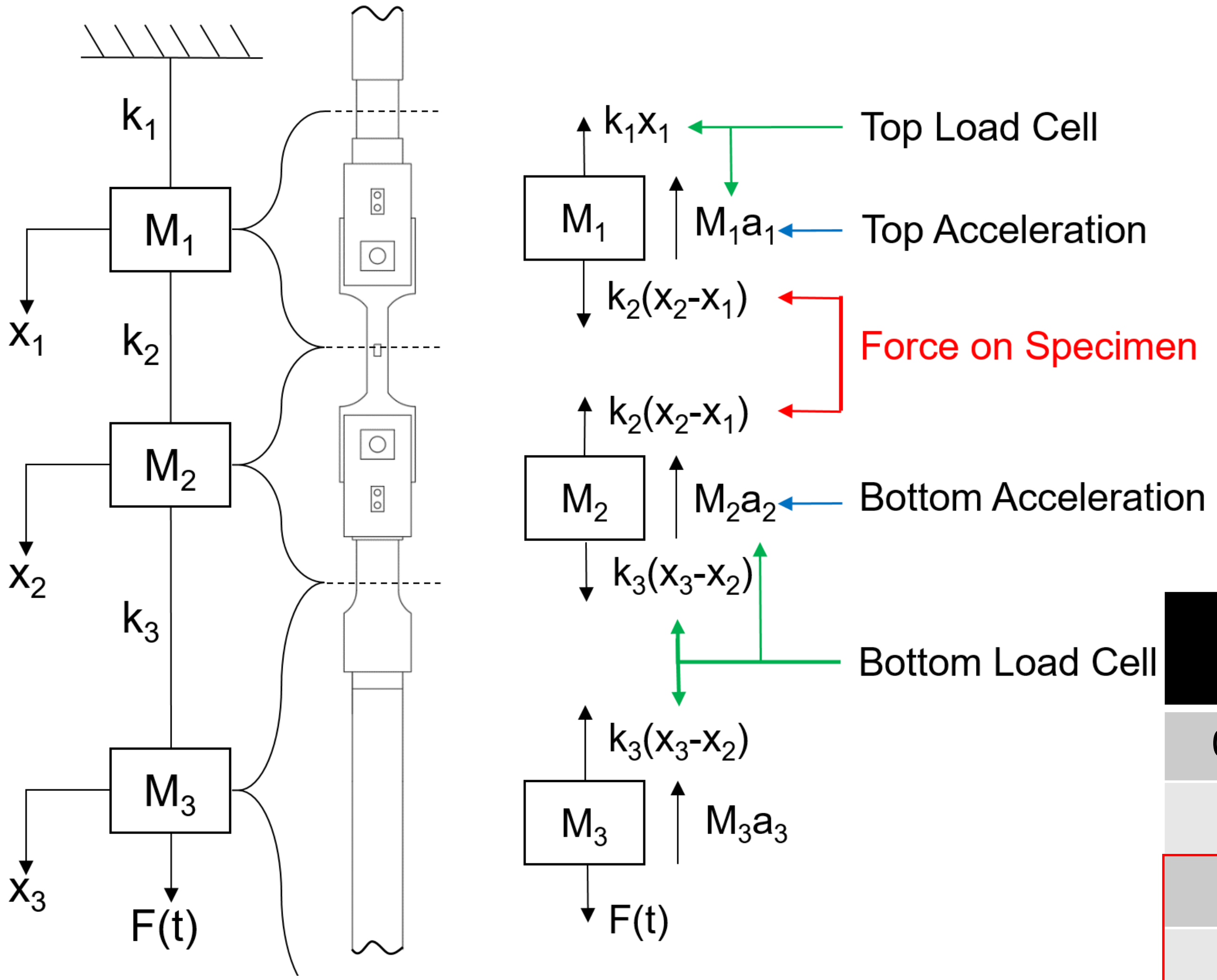
Phantom Miro 320S High Speed Camera

Correction for Inertial Effects

$$k_2(x_2 - x_1) = M_1 a_1 + k_1 x_1$$
$$\Rightarrow k_2(x_2 - x_1) = k_1 x_1 - M_1 a_1$$

$$k_3(x_3 - x_2) = M_2 a_2 + k_2(x_2 - x_1)$$
$$\Rightarrow k_2(x_2 - x_1) = k_3(x_3 - x_2) - M_2 a_2$$
$$\Rightarrow k_2(x_2 - x_1) = k_3(x_3 - x_2) + M_2 a_2$$

$$F(t) = M_3 a_3 + k_3(x_3 - x_2)$$

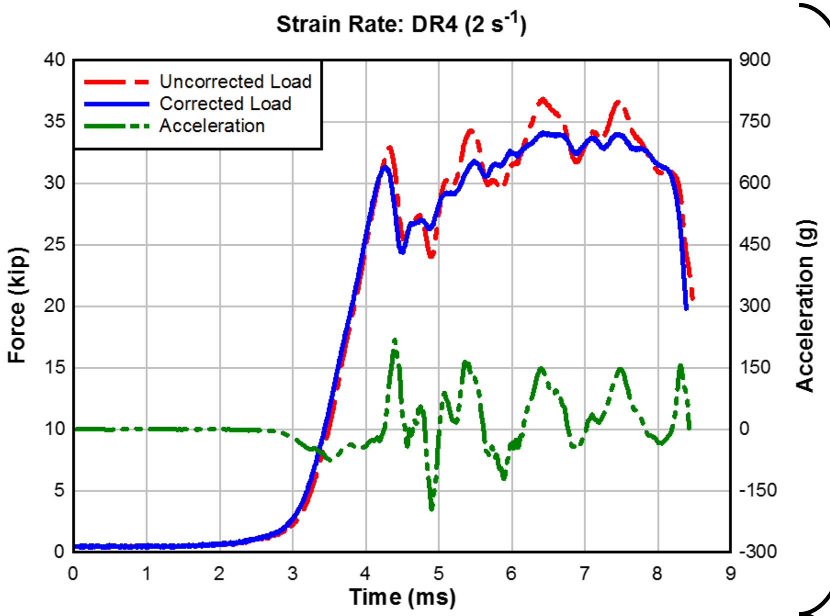


Accelerometers mounted in opposite orientation

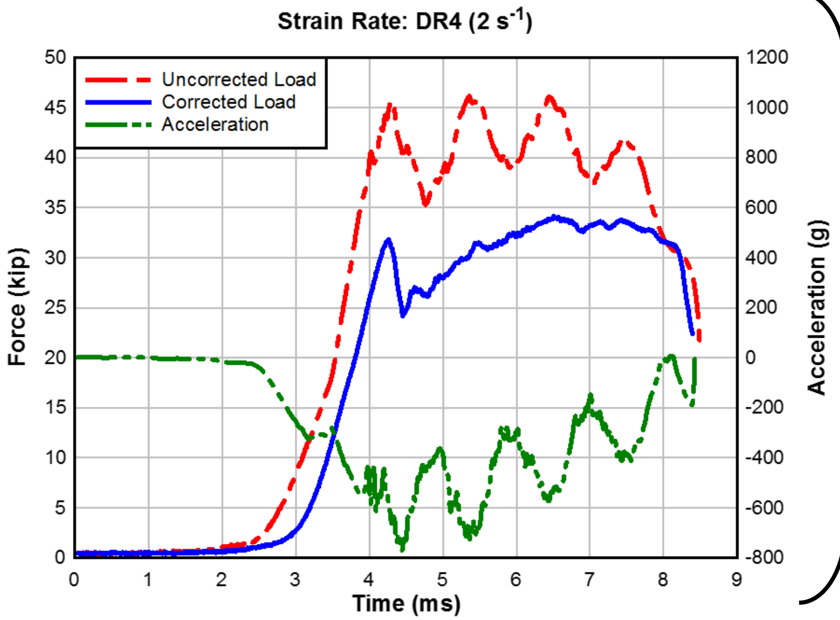
Uncoupled (mass) Spring-Mass Model

Tested Strain Rates (s^{-1})	
0.00002	SR
0.002	DR1
0.05	DR2
0.2	DR3
2.0	DR4

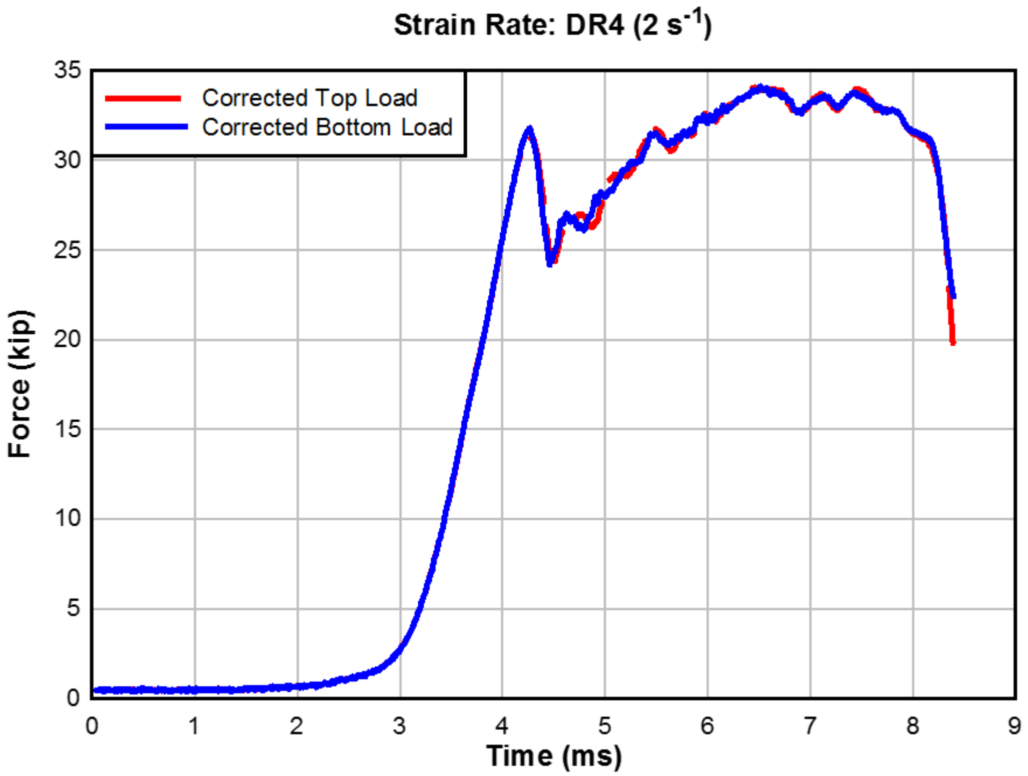
Force Correction and Stress Calculation



Top Load Correction



Bottom Load Correction



Engineering stress versus time:

- Average corrected load versus time and original cross-sectional area

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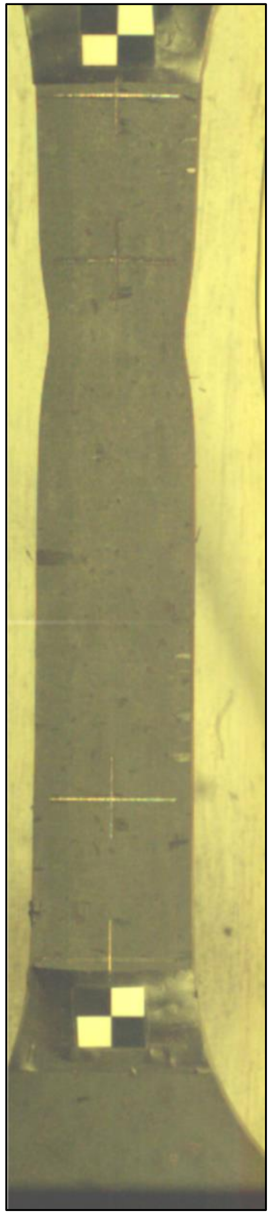
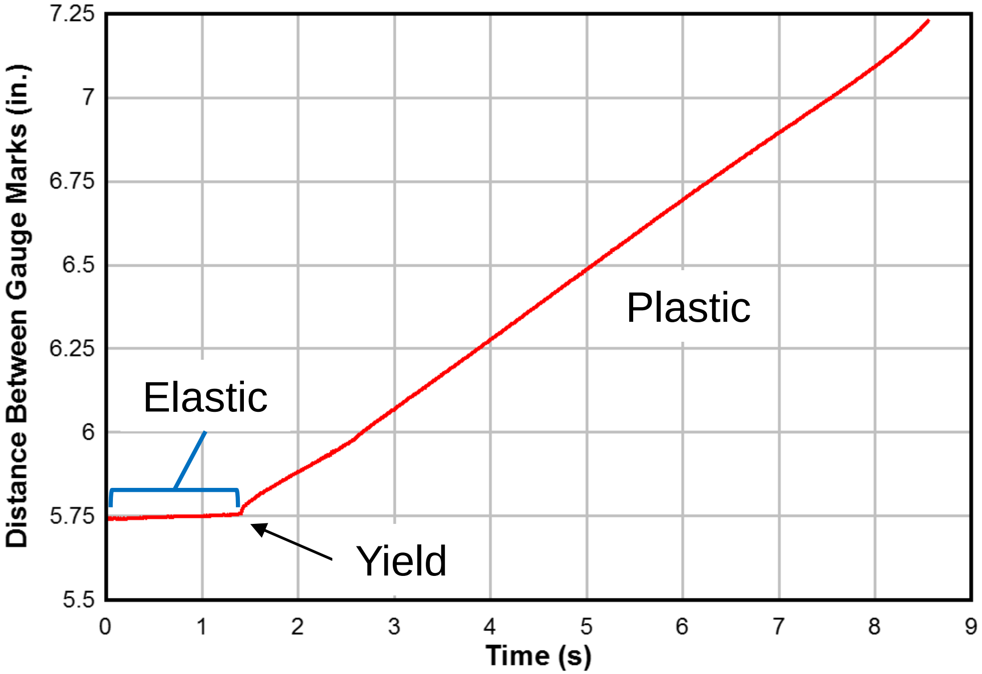
Strain Calculation



Engineering Strain:
- TrackEye Motion Analysis (TEMA) software by Image Systems AB
- Average strain and elastic strain rate calculated using elongation and original gauge length

TEMA Elongation Output



Vertical Resolution:
1,200 pixels: DR1-2
904 pixels: DR3-4

Pixel Length:
0.00105 in. [0.027 mm]: DR1-2
0.00155 in. [0.039 mm]: DR3-4

Strain Accuracy:
0.00018 (180 microns): DR1-2
0.00025 (250 microns): DR3-4

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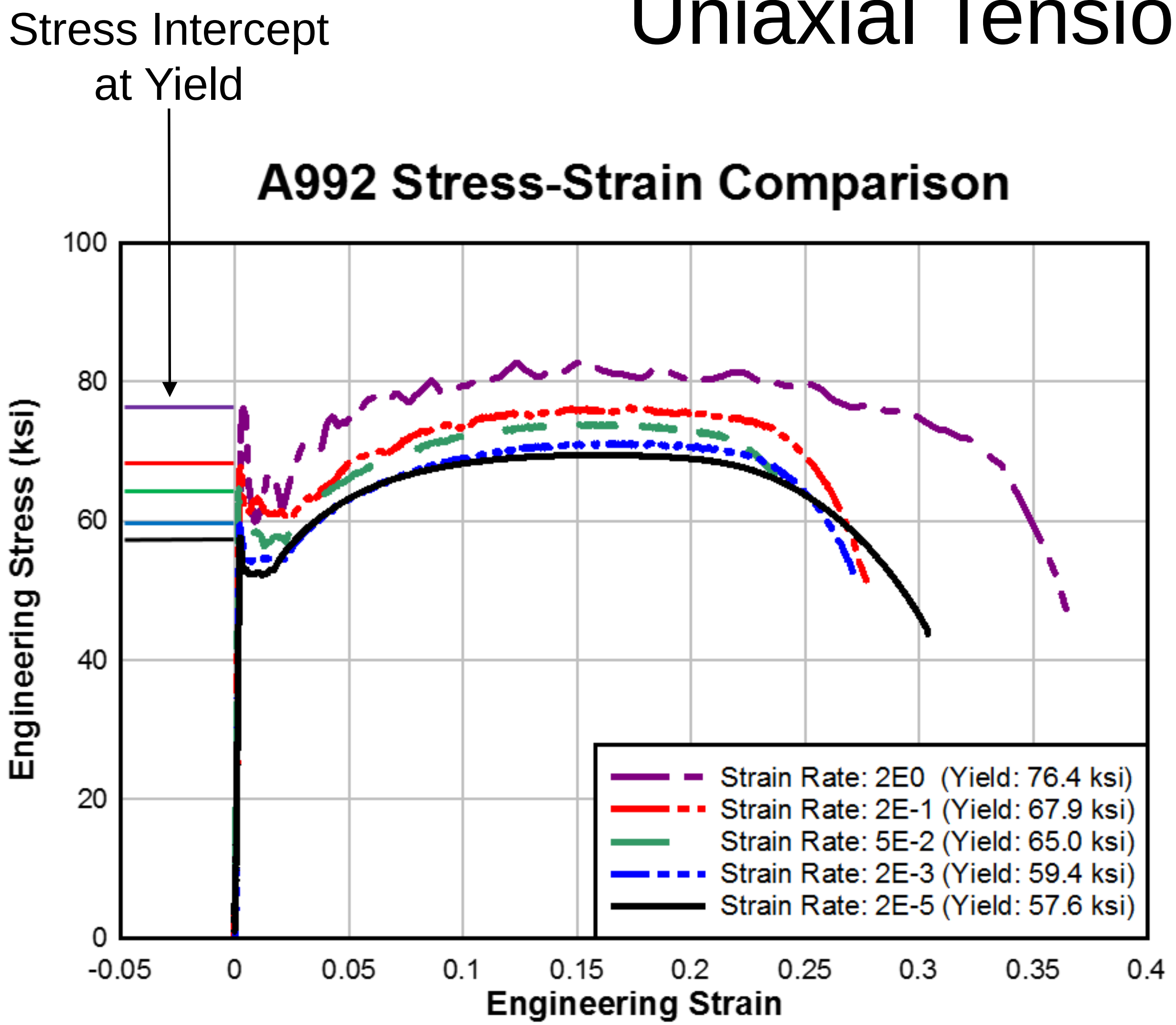
Uniaxial Tension Test Results



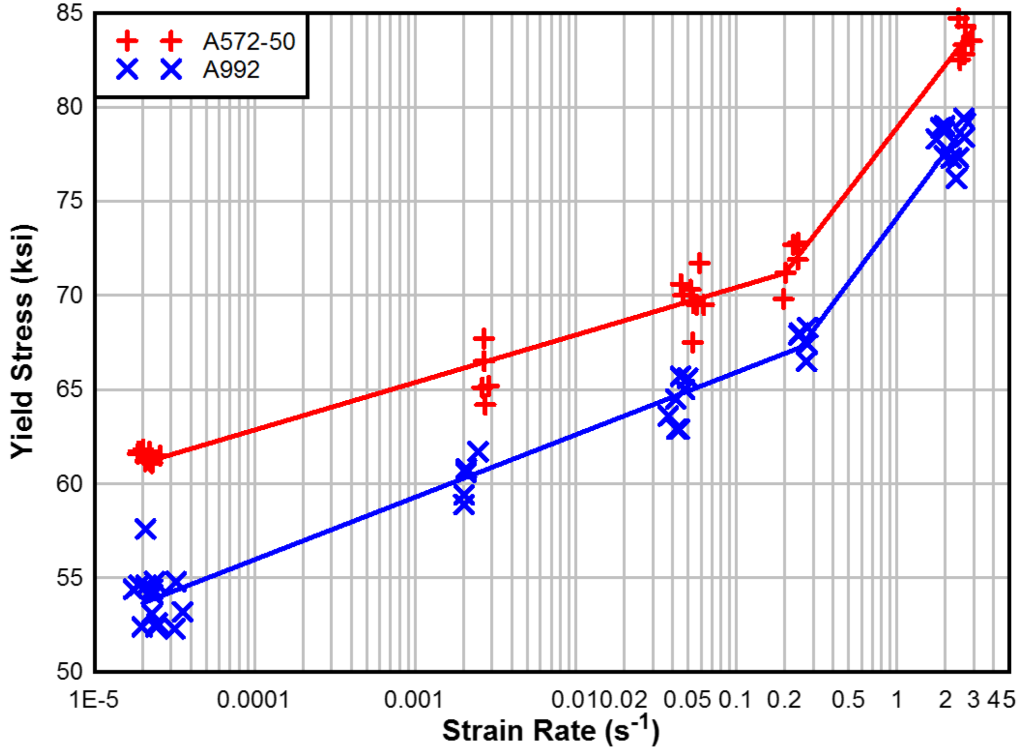
Strain Rate (s^{-1})		# of Tests A992	# of Tests A572-50
0.00002	SR	14	8
0.002	DR1	5	5
0.05	DR2	7	8
0.2	DR3	5	5
2.0	DR4	11	6

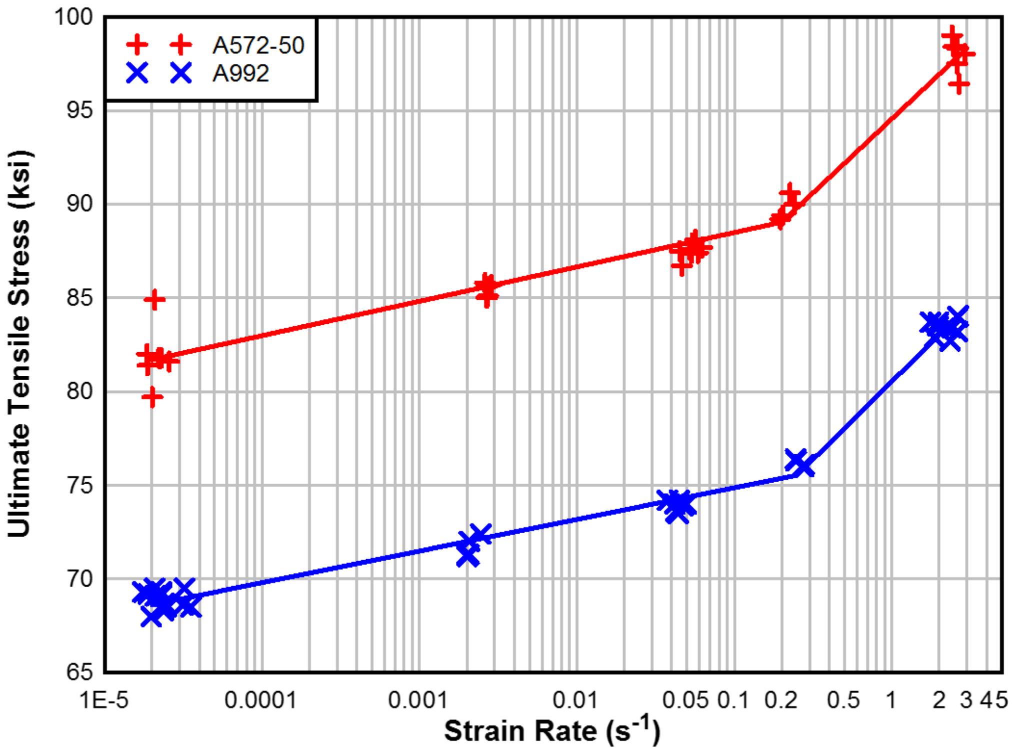
Increased strain rate →

- Increased yield strength
- Increased ultimate tensile strength (UTS)
- Unchanged modulus of elasticity
- Unchanged or slightly reduced elongation at rupture

→Increased elongation

Experimental Results

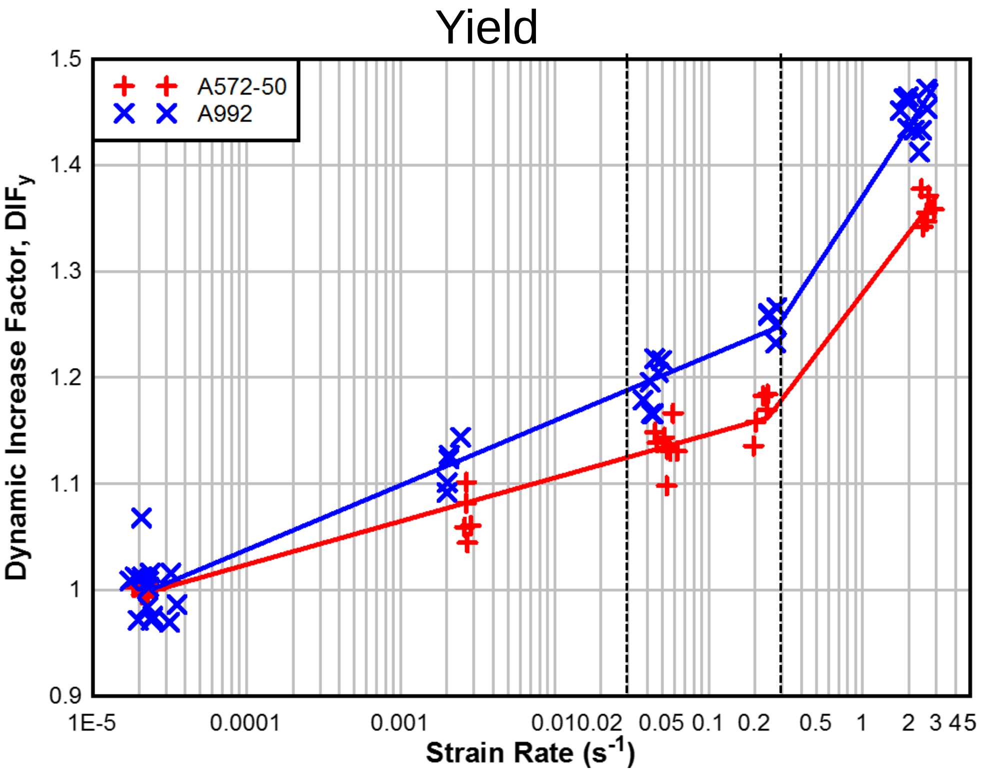


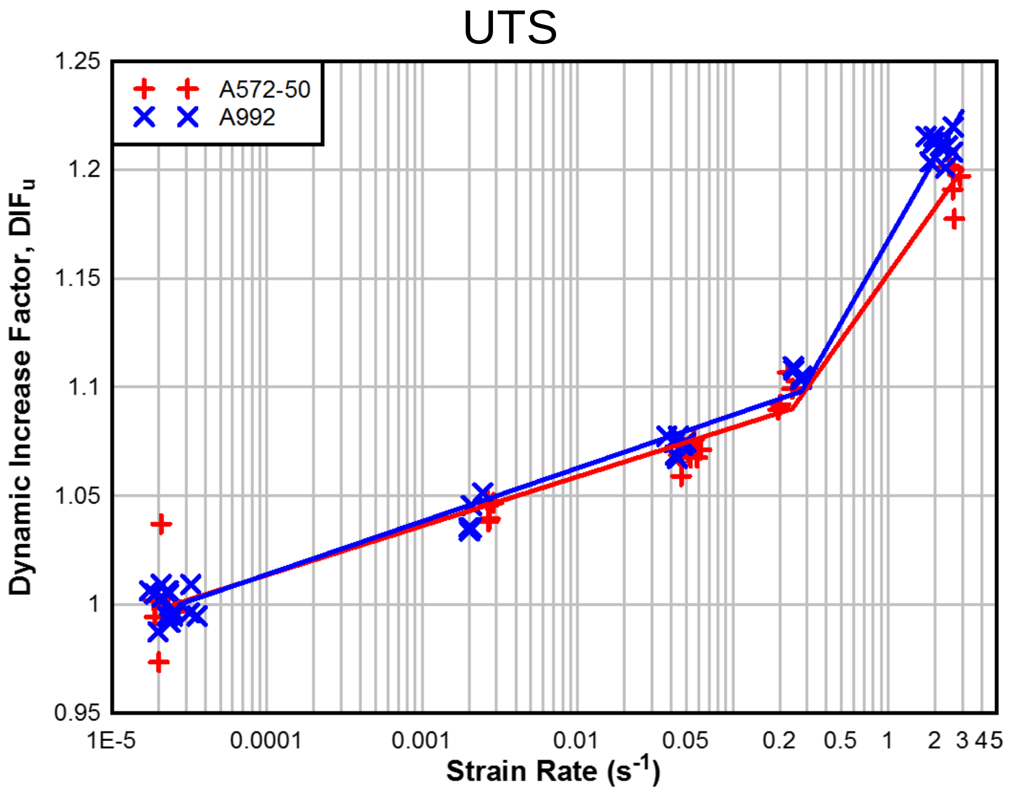


Material	Average Static Yield Strength	Yield Strength Increase (2.0 s^{-1})
A572-50	64.5 ksi	35%
A992	54.0 ksi	45%

Material	Average Static UTS	UTS Increase (2.0 s^{-1})
A572-50	81.9 ksi	20%
A992	68.9 ksi	20%

Experimental Dynamic Increase Factor



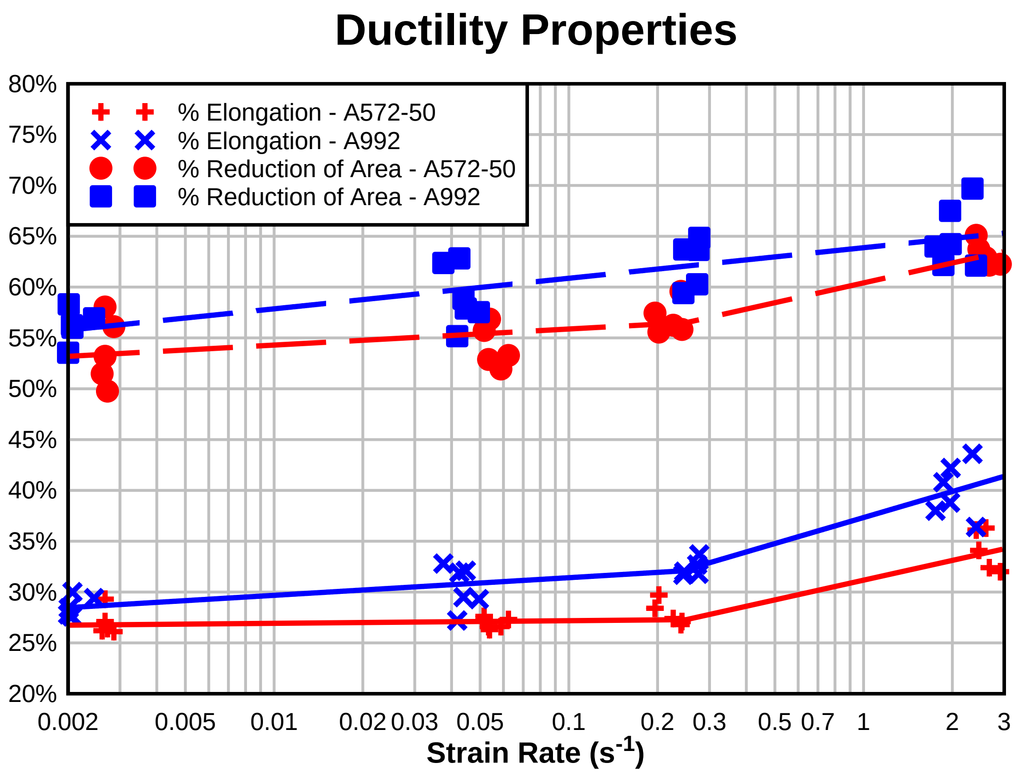


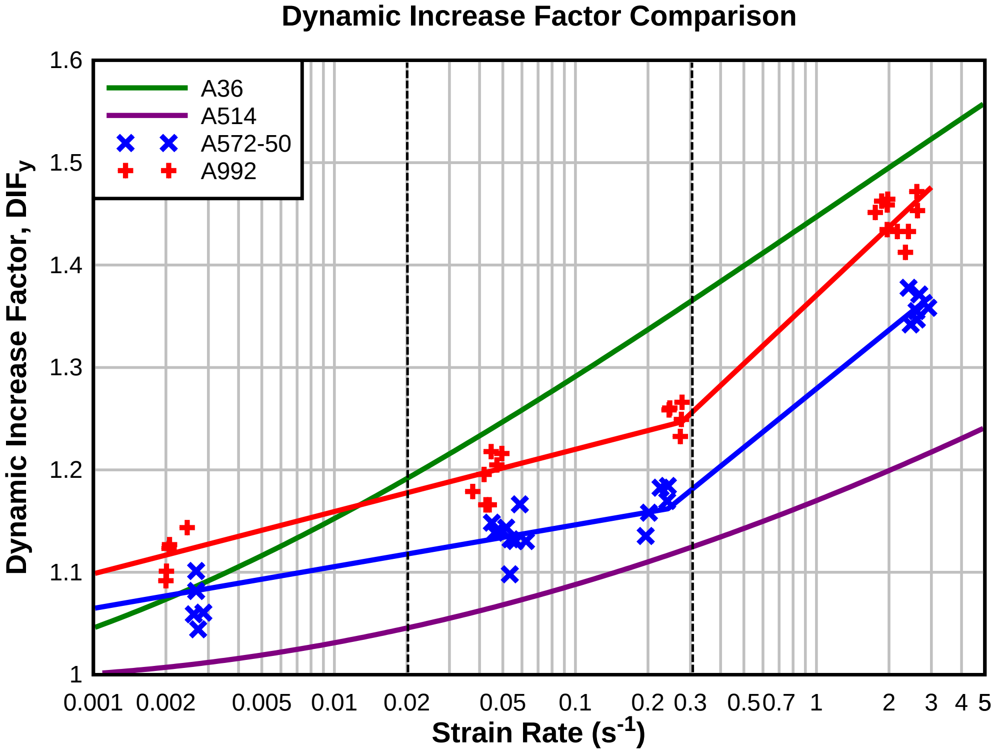
Different strain rate sensitivities:

- Dependent on static yield strength
- Malvar and Crawford → UFC reinforcing steel guidelines (4-13.2)

Malvar, L. J., and J. E. Crawford. "Dynamic Increase Factors for Steel Reinforcing Bars." Port Hueneme, CA: Naval Facilities Engineering Service Center, August 1998.

Ductility Properties and DIF Comparison



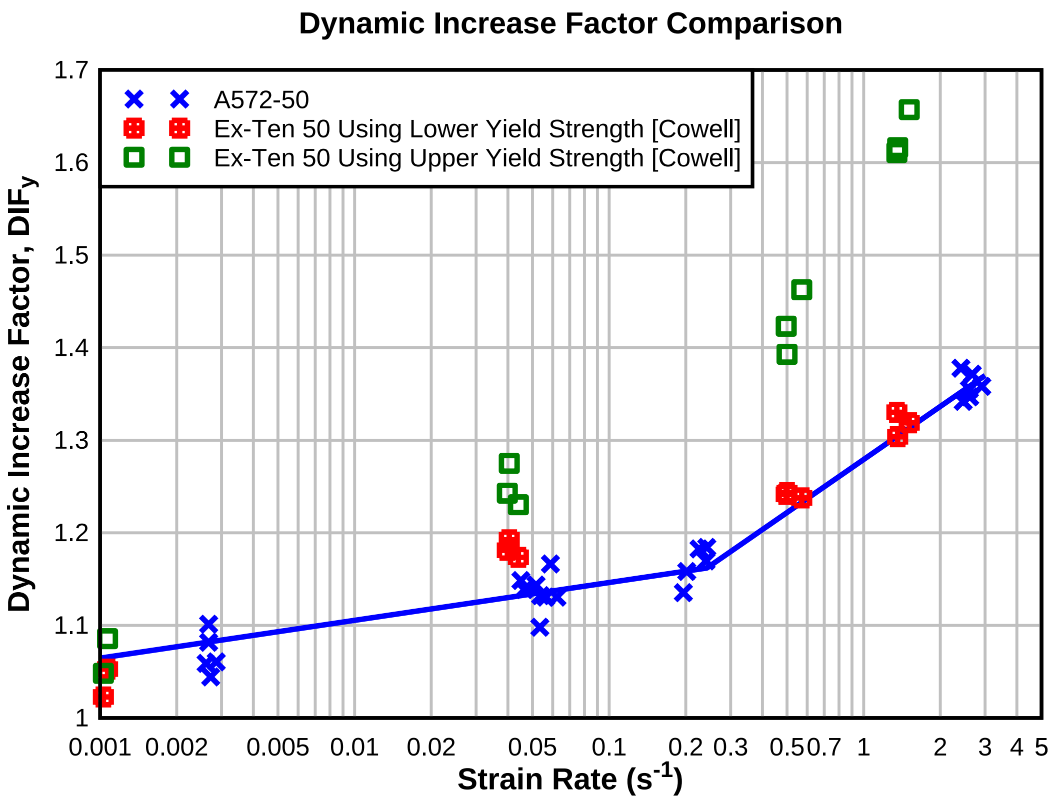


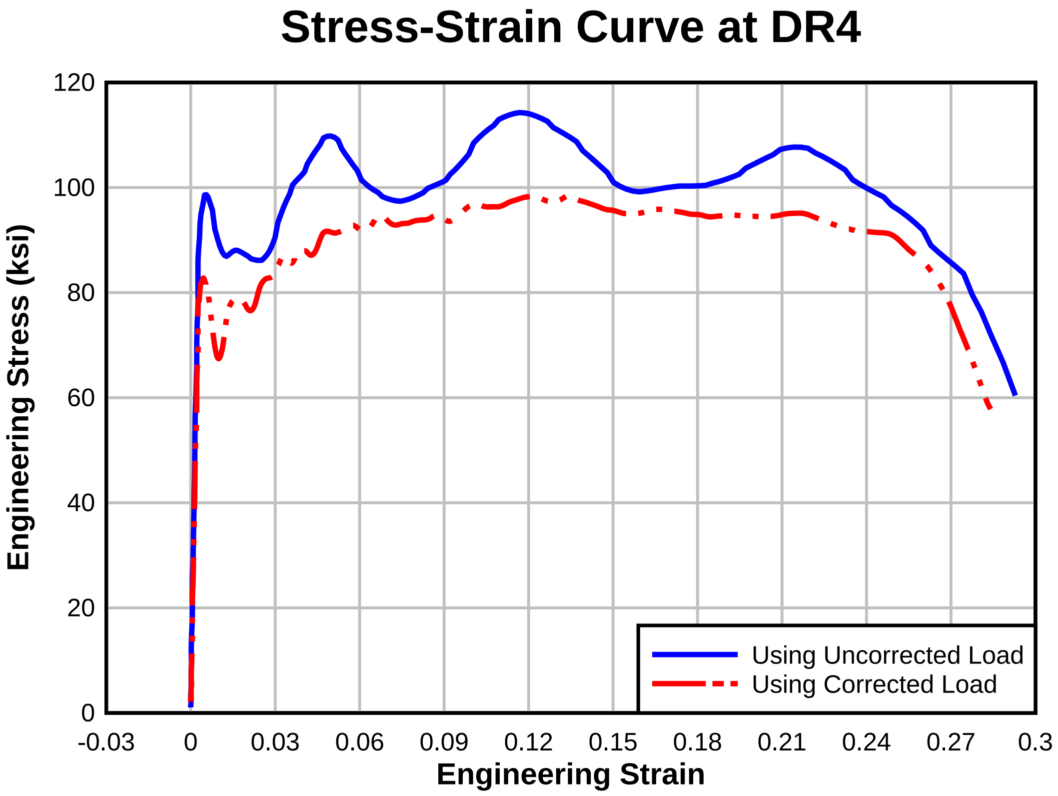
- Increase of ductility properties with strain rate*
- Experimental DIF_y values between A36 and A514 design *DIF* curves at typical design rates (between dotted grid lines)

Comparison of Experimental Results

- Ex-Ten 50 tested by Cowell in 1969
- Ex-Ten 50 representative of A572-50
- Inertial effects neglected for Cowell's experiments
- Cowell reported DIF_y calculated with lower yield strength

Cowell, W. L. "Dynamic Tests on Selected Structural Steels." Technical Report R 642. Port Hueneme, CA: U.S. Naval Civil Engineering Laboratory, September, 1969.





Conclusions

- Dynamic properties of A572-50 and A992 were determined and compared to static values
- Experimental dynamic increase factors were calculated
- A bi-linear, least-squares fit DIF curve was developed for each steel at increasing strain rates
- Design *DIF* and *c* curves are being developed from experimental values for implementation into UFC 3-340-02

Recommendations

- Conduct research on foreign produced steel that meets A572-50 and A992 specifications
- Conduct research on other foreign specified steels that may be used in protective construction

Questions?

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ERDC is the approved validation facility for mechanical splices of reinforcement used in protective design:
UFC 3-340-02, Chapter 4-21.8.

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