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Digital Image Correlation (DIC) Method for Strain Measurement of Corroded Weathering Steel

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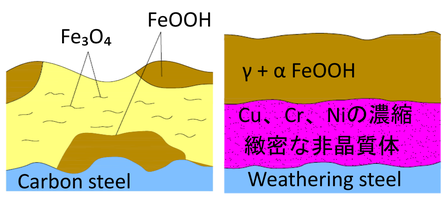
Research Aims and Objectives: A non-destructive strain detection method for corrosion-induced roughened steel surfaces is essential for ensuring the safety and long-term serviceability of civil infrastructure. This study evaluates the effectiveness of the Digital Image Correlation (DIC) method for strain measurement on corroded weathering steel.

〈Weathering Steel in Bridges〉

Chemical composition of weathering steel

Steel type	Chemical composition (% by weight)									
	C	*Si*	*Mn*	*P*	*S*	*Cu*	*Cr*	*Ni*	*Nb*	*V*
SM	0.17	0.32	1.39	0.01	0.01	-	-	-	-	-
SMAW	0.12	0.39	0.9	0.01	0.01	0.36	0.61	0.22	0.01	-

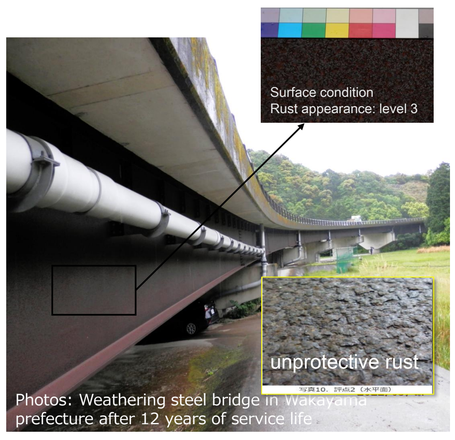
Formation of protective rust in proper environment



$$4Fe + 3O_2 + nH_2O \rightarrow 2Fe_2O_3.nH_2O$$

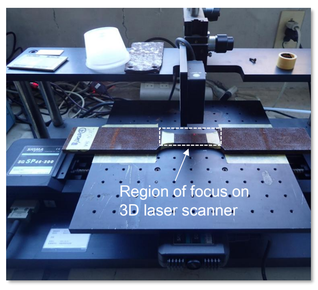
Dehydrate ↓ *Cu, Cr, Ni dense rust*

$$\gamma - FeOOH \rightarrow \alpha - FeOOH$$

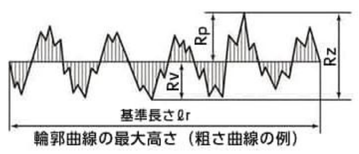


〈Surface Roughness Evaluation〉

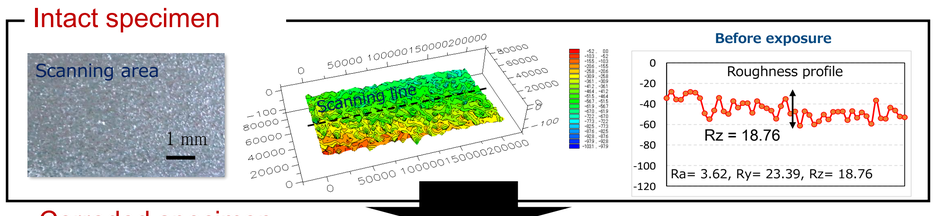
Remove the rust layer from the produced corroded specimen and measure for the surface roughness.



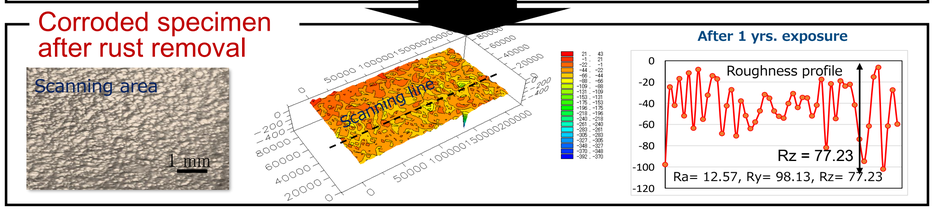
$$R_z = R_v + R_p$$



Intact specimen



Corroded specimen after rust removal



Test period (months)	Rust thk., μm	Roughness (μm)		
		Ra	Ry	**Rz**
0	0	3.62	23.39	**18.76**
7	68.7	11.38	90.23	**64.66**
12	102.7	**12.57**	**98.13**	**77.23**

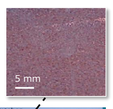
〈Corroded sample production〉

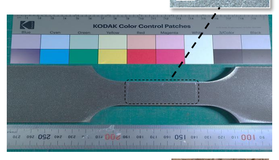
Exposure test conditions

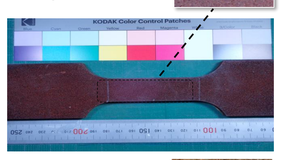
SMA 400W

Original surface

4 months
Avg. rust thk.
39 μm

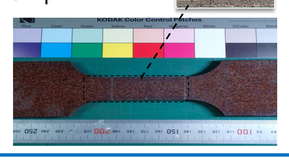


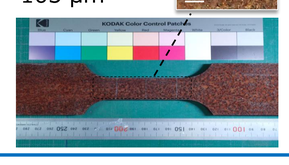




7 months
Avg. rust thk.
67 μm

12 months
Avg. rust thk.
103 μm





Specimen type	No. 5 specimen, JIS Z 2241
Test duration	0, 4, 7, 12 months

Test location	Nago city, Okinawa
Corrosive environment	Coastal
Weather conditions	
Annual T	Min: 11 ºC, Max: 35 ºC
Annual RH	Min: 42%, Max: 99%
Airborne salt	1 mdd < Cl^- < 10 mdd

〈Camera〉

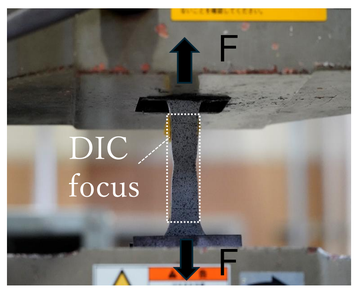
Sony Alpha 7

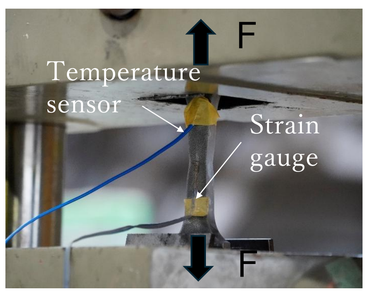
Resolution: 24 MP
Frame size: 5 fps
(ISO 50-25600)
Working dis. < 1m

Min shutter speed: 30 s
Max. image resolution:
6000 × 4000
Video resolutions: 1920 × 1080

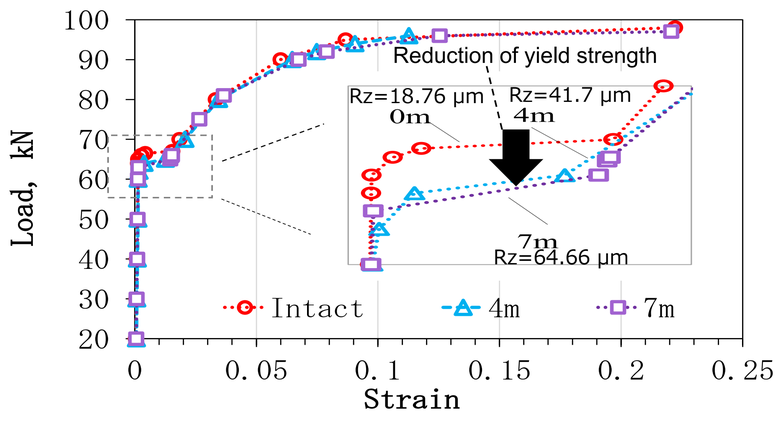
〈Uniaxial Tensile Test〉

Analytical specimen surface for DIC





Test machine/ capacity	Tokyo KOKI UTM 10t (Kyoto Uni.)
Loading condition	Statistic, 1 MPa/s in elastic state and 0.1 MPa/s in plastic state



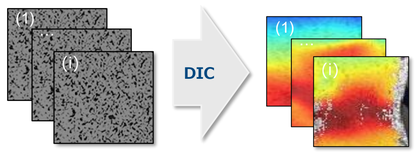
〈The DIC Method〉

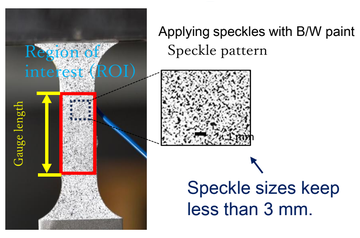
Flow chart of DIC

1. Pitting and surface abnormalities identification
2. Creating an artificial or natural speckles
3. Record photos/ videos during tensile loading
4. Digital Image Correlation by Newton-Raphson method using MATLAB (Ncorr)

Strain calculation method from deformed speckle

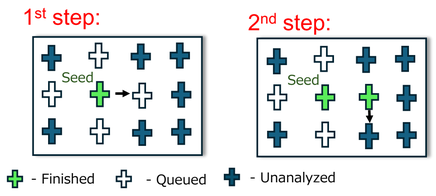
Conversion of reference subsets to 2D DIC



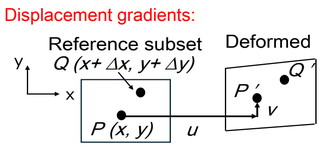


1st step:

2nd step:



Displacement gradients:



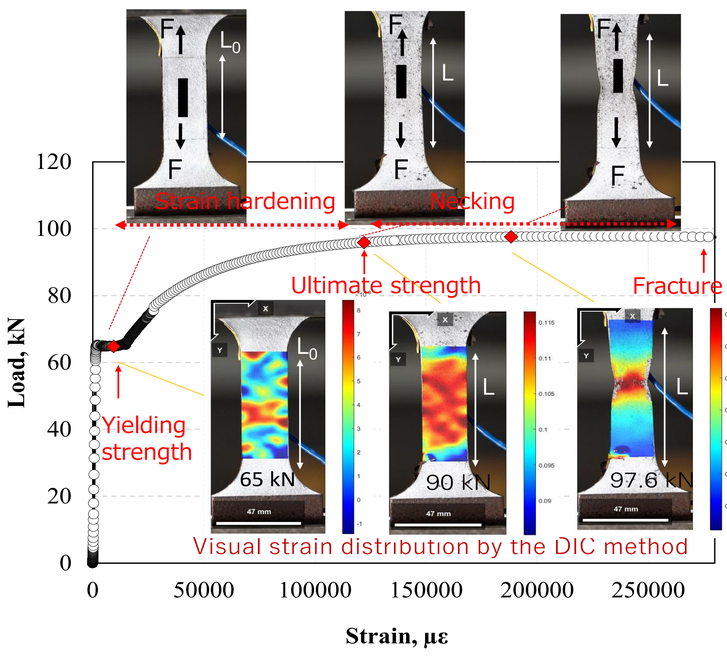
Green-Lagrangian strain: $E_{xx} = \frac{1}{2}\left(\frac{2\partial u}{\partial x} + \left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2\right)$, $E_{xy} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + \frac{\partial u}{\partial x}\frac{\partial v}{\partial y} + \frac{\partial v}{\partial x}\frac{\partial u}{\partial y}\right)$, $E_{xx} = \frac{1}{2}\left(\frac{2\partial v}{\partial y} + \left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right)$

$$x_q = u_p + \frac{\partial u_p}{\partial x}\Delta x_q + \frac{\partial u_p}{\partial y}\Delta y_q \ldots\ldots\ldots(1)$$

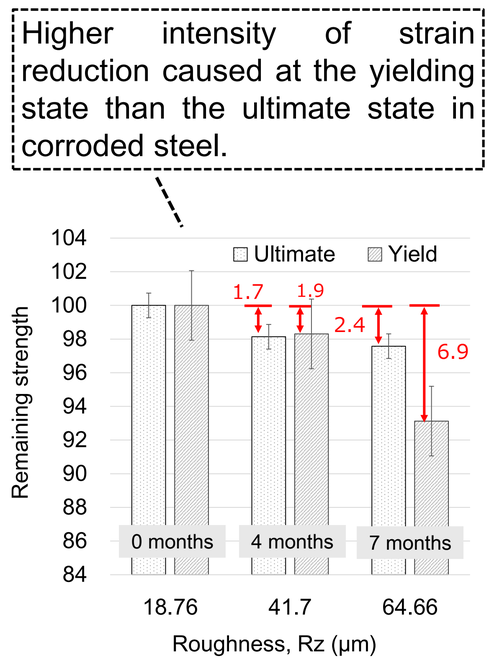
$$y_q = v_p + \frac{\partial v_p}{\partial y}\Delta y_q + \frac{\partial v_p}{\partial x}\Delta x_q \ldots\ldots\ldots(2)$$

〈Result.1 Strain Distribution Map〉

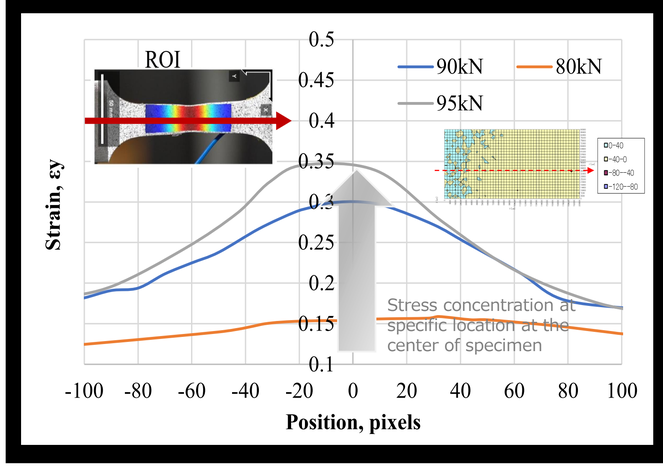
Specimen condition during tensile test

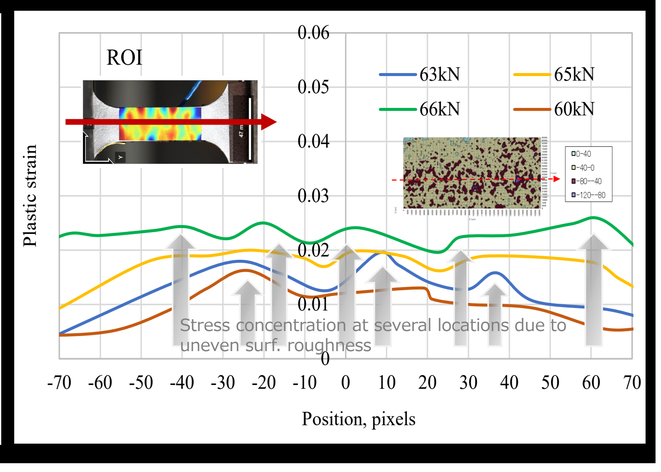


Higher intensity of strain reduction caused at the yielding state than the ultimate state in corroded steel.



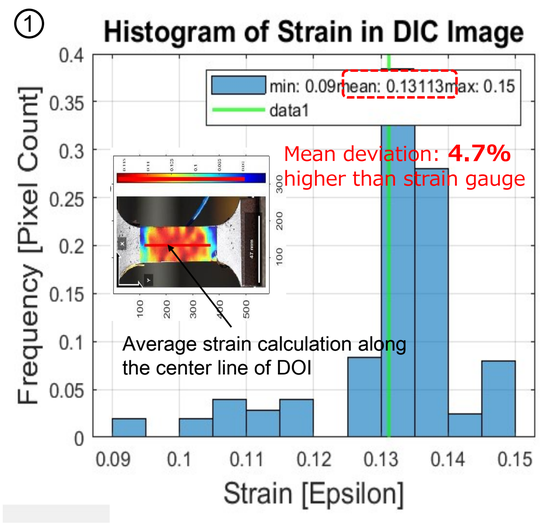
Strain distribution pattern of intact and corroded specimen

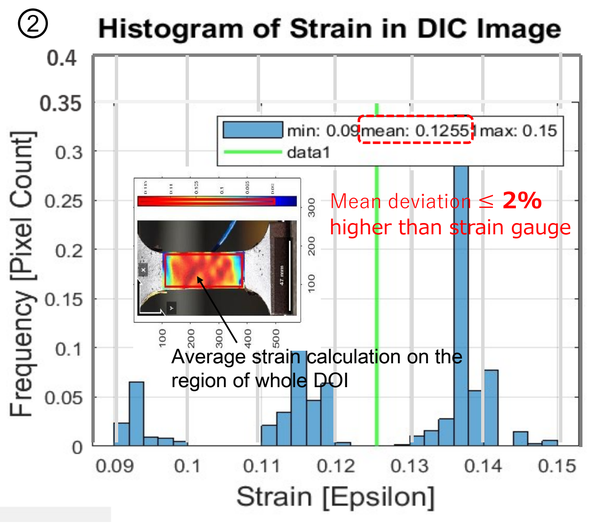




〈Result.2 Validation of DIC strain〉

Influence of ROI on strain measurement accuracy





Comparison of DIC strain vs. strain from physical strain gauge ①

Surface roughness, μm	18.7	64.6	77.2
R^2	0.986	0.944	0.876

〈Discussion and Conclusions〉

- Surface roughness due to corrosion reduces the yield and ultimate strength of steel by approximately 7% and 3%, respectively, as measured by DIC and physical gauges after seven months of exposure in Okinawa.
- Non-uniform yielding was observed on the surface of weathering steel corroded during one year of exposure in Okinawa.
- The full-field strain distribution map by the DIC method provides the capability to identify localized stress concentrations caused by the uneven steel surface.

<u>Future work: Further improvement of the DIC analysis method for application to in-service weathering steel bridges.</u>