INVESTIGATION OF THE TENSILE/COMPRESSIVE RESIDUAL STRESSES IN AISI 4340 STEEL UNDER LOW-CYCLE FATIGUE LOADING

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Introduction

- Fuse pins serve as a safety feature within the landing gear of an aircraft to reduce structural damage in the event of a hard landing. To do this, fuse pins are designed with an inner circumferential notch to absorb energy and promote failure at the notch once a predetermined load is exceeded.
- The inclusion of a notch creates a location of complex stress, causing local yielding under an applied load and making accurate fatigue life predictions challenging to achieve, particularly under unexpected loading events such as overload.
- An industry assumption to account for the residual stress formed by overload is to equate the residual stress to a mean stress. However, the validity of this assumption has not been well-studied in literature, particularly for low-cycle fatigue loading [1].
- This work utilizes the strain-life method to study the low-cycle fatigue life of notched AISI 4340 steel components, to study the effects of complex residual stresses, and to investigate the applicability of the residual stress – mean stress design assumption.

Methodology

- Six quasi-static tensile tests were completed to determine average tensile properties, from which strain life coefficients were estimated according to [2].
- Fatigue specimens were subjected to either fully-reversed low-cycle fatigue loading (baseline samples), quasi-static initial overload prior to fully-reversed fatigue testing, or low-cycle fatigue loading with a mean stress of identical magnitude as the residual stress induced from the initial overload.
- A finite element model was developed using ABAQUS 2021x to determine the residual stress relative to distance from the notch root. This model was used to determine the load in the previous step to achieve a given maximum residual stress at the notch root.

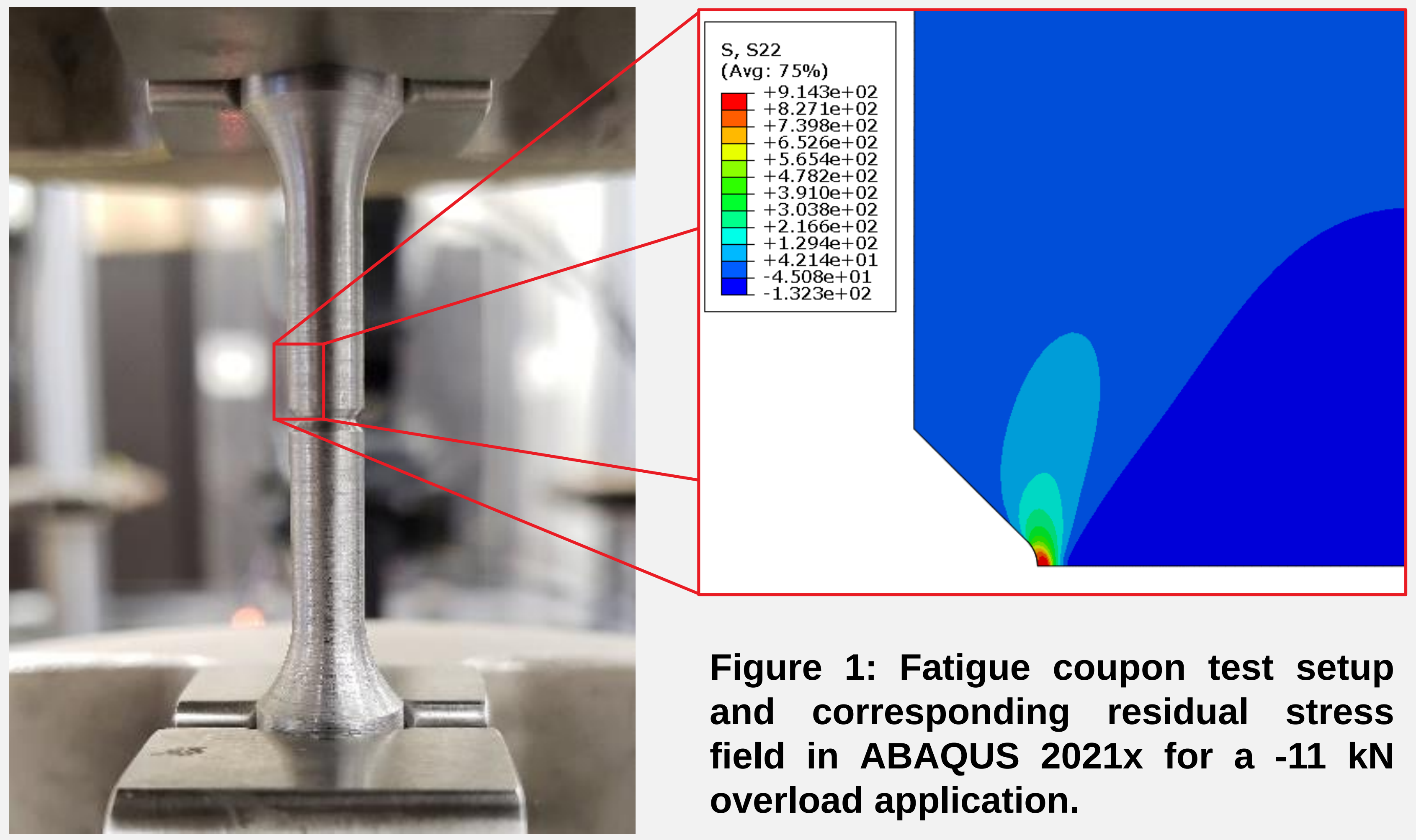

Figure 1: Fatigue coupon test setup and corresponding residual stress field in ABAQUS 2021x for a -11 kN overload application.

Results

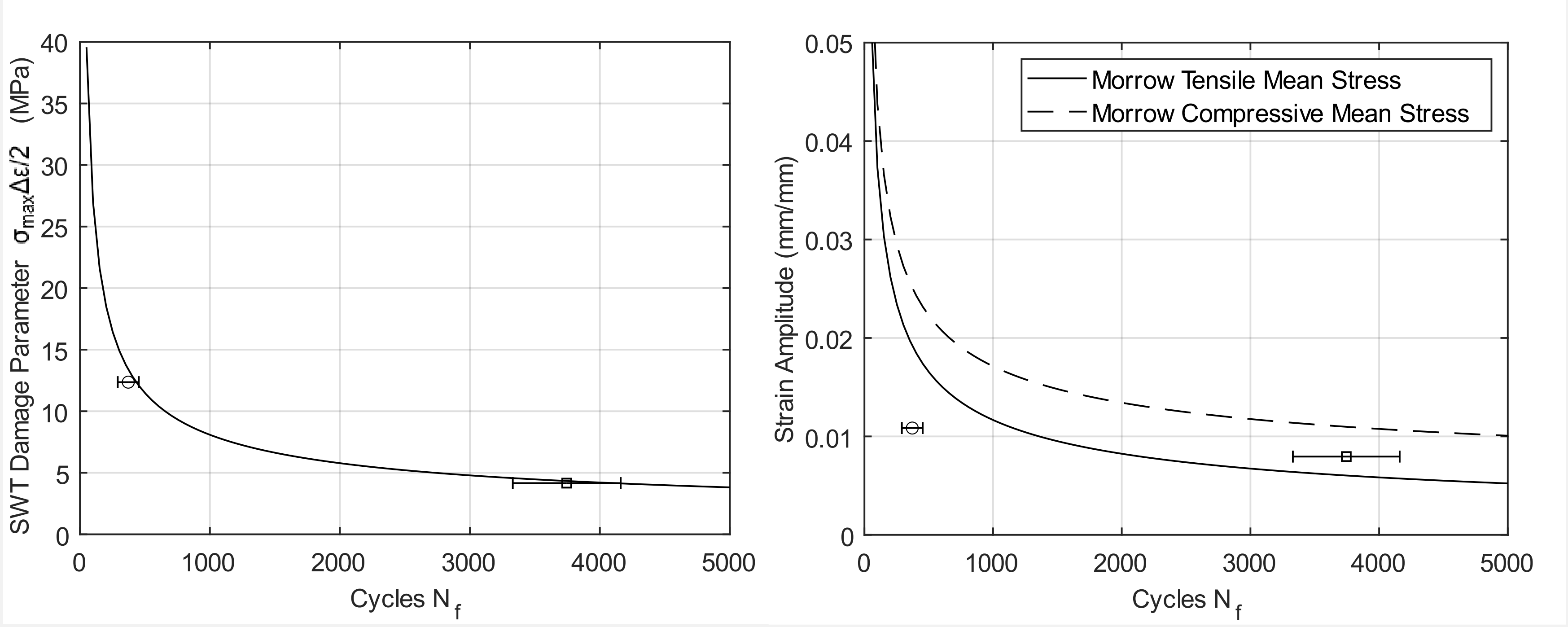

Figure 2: Experimental mean stress coupon data compared to the predictive Smith-Watson-Topper (SWT) model (left) and the Morrow mean stress correction model (right).

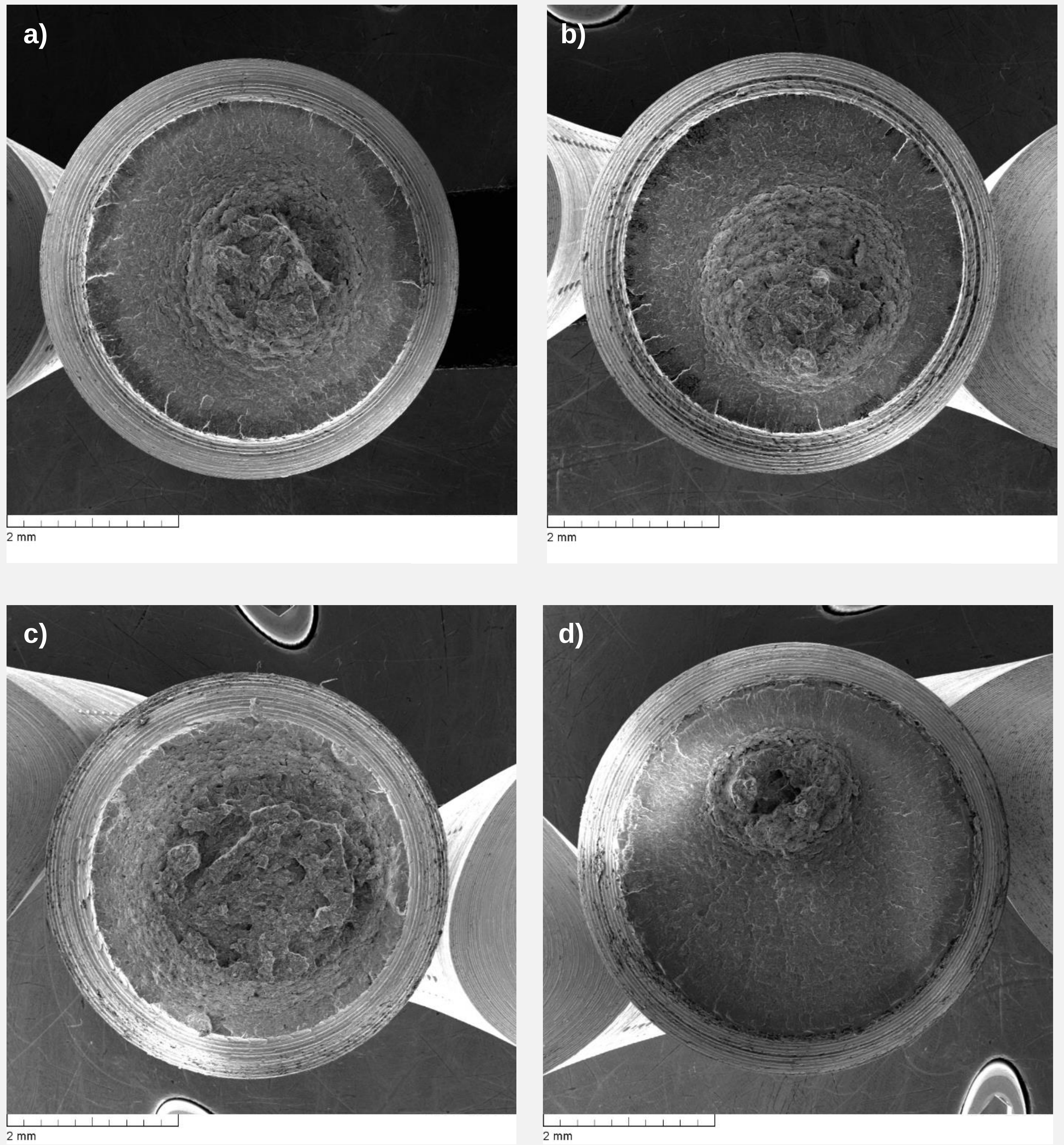

Figure 3: SEM images for specimens with a) a tensile overload, b) a compressive overload, c) a tensile mean stress, and d) a compressive mean stress.

Strain Life Prediction Models

Strain-Based Fatigue Life Estimation:

$$\frac{\Delta\varepsilon}{2} = \underbrace{\frac{\sigma_f'}{E}\left(2N_f\right)^b}_{\text{elastic}} + \underbrace{\varepsilon_f'\left(2N_f\right)^c}_{\text{plastic}}$$

Smith-Watson-Topper Mean Stress Correction:

$$\sigma_{\max}\frac{\Delta\varepsilon}{2} = \underbrace{\frac{{\sigma_f'}^2}{E}\left(2N_f\right)^{2b}}_{\text{elastic}} + \underbrace{\sigma_f'\varepsilon_f'\left(2N_f\right)^{b+c}}_{\text{plastic}}$$

Morrow Mean Stress Correction:

$$\frac{\Delta\varepsilon}{2} = \underbrace{\frac{\sigma_f'-\sigma_m}{E}\left(2N_f\right)^b}_{\text{elastic}} + \underbrace{\varepsilon_f'\left(2N_f\right)^c}_{\text{plastic}}$$

Conclusions

- The design assumption of equating the local residual stress to a mean stress for low-cycle fatigue life analysis of notched AISI 4340 steel is generally a nonconservative estimate and should be avoided.
- Fatigue life results from load-controlled testing demonstrated good agreement with strain life methodologies, which is consistent with previous literature [1, 3-4]
- Tensile overloads caused a 5% increase in low-cycle fatigue life while compressive overloads caused a 23% reduction in low-cycle fatigue life.
- The Smith-Watson-Topper model and the Morrow mean stress correction model both provided nonconservative estimates for tensile mean stress and compressive mean stress coupons, although the Smith-Watson-Topper method provided more accurate fatigue life predictions.
- Predictive results are highly dependent on fatigue ductility exponent *c* in the low-cycle fatigue regime.
- Initial overloads had an impact in only the crack initiation phase, while mean stresses affected the size of the crack propagation region.

References

[1] Bassindale, C., Miller, R. E., and Wang, X. (2020), Int. J. Fatigue, n. 130, 105273.

[2] Lee, Y.-L., Pan, J., Hathaway, R. and Barkey, M. (2005). In: Fatigue Testing and Analysis (Theory and Practice), pp. 219-220, Elsevier, Burlington.

[3] Fash, J. and Socie, D. F. (1982), Int. J. Fatigue., vol. 4, n. 3, p. 137-142.

[4] Colin, J., Fatemi, A. and Taheri, S. (2010), J. Eng. Mater. Technol., vol. 132, n. 2, 021008.

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