Supplementary Materials

Prediction of Corrosion and Related Damage States in High-Temperature Equipment Using Mechanism and Data Fusion

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Supplementary Figures

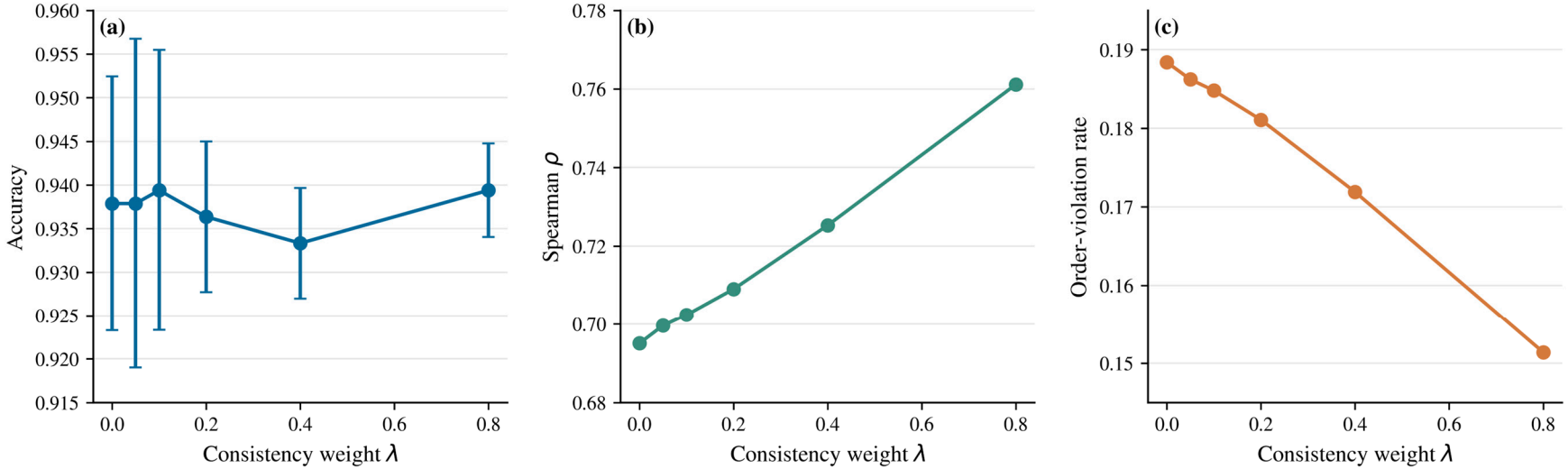


Figure S1. Sensitivity to the mechanism-consistency weight λ. (a) Accuracy with five-fold standard deviations. (b) Spearman correlation between predicted severity and the label-independent physical trend index. (c) Prediction-order violation rate.

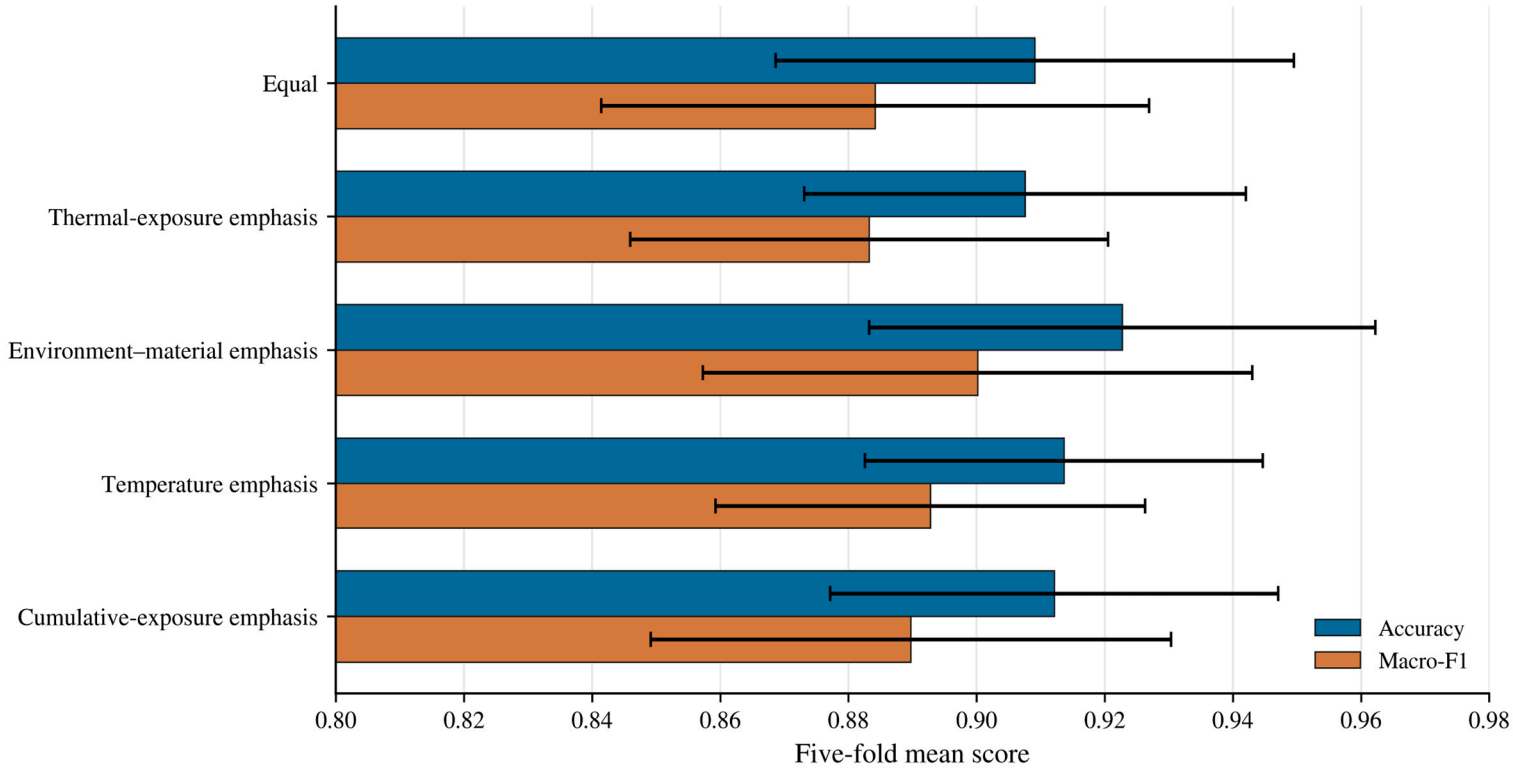


Figure S2. Sensitivity to the weighting scheme of the comprehensive damage-driving index. Error bars show five-fold standard deviations. The equal-weight setting assigns 0.25 to each component.

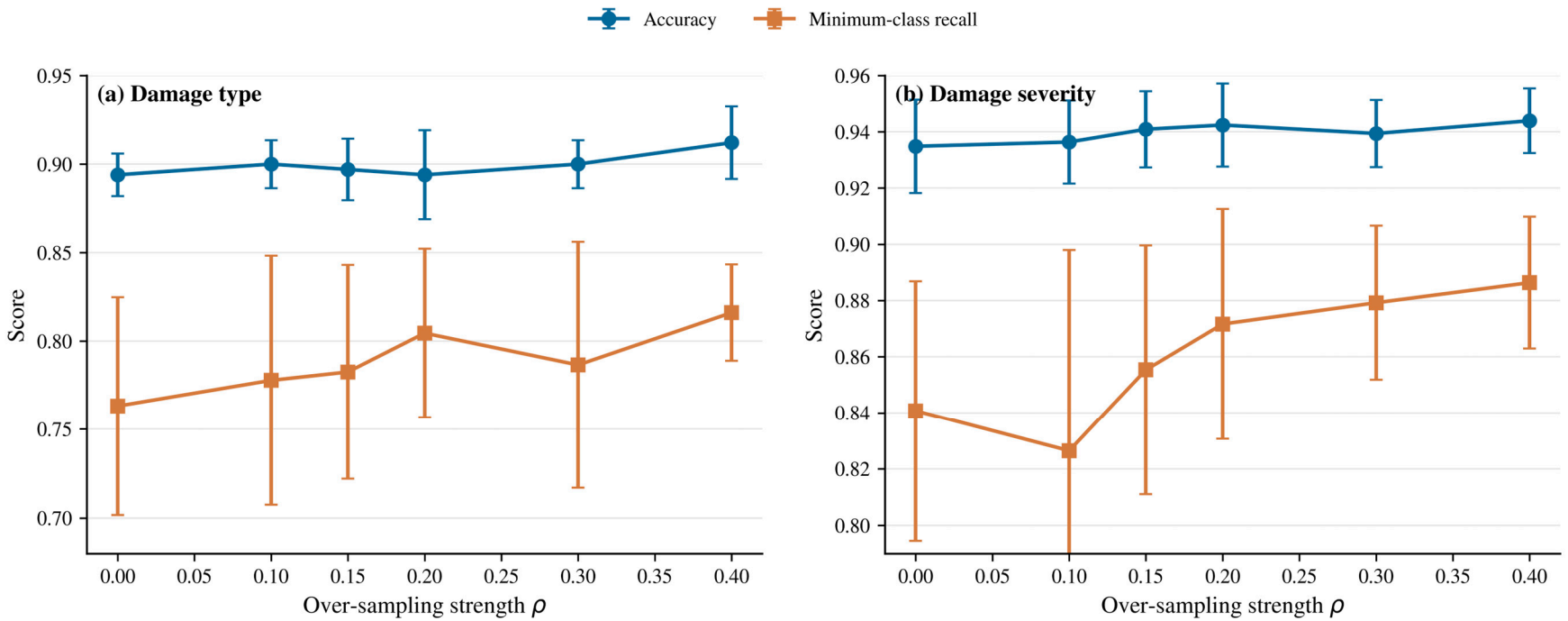


Figure S3. Sensitivity to partial random over-sampling strength ϱ for (a) damage-type classification and (b) damage-severity prediction. Error bars show five-fold standard deviations. The main experiments used ϱ = 0.30 for damage type and ϱ = 0.15 for damage severity.

Supplementary Tables

Table S1. Complete numerical results of the sensitivity analyses.

Table S1a Consistency weight

λ	Accuracy	Macro-F1	Ordinal MAE	Spearman ρ	Order-violation rate
0.00	0.9379 ± 0.0146	0.9276 ± 0.0218	0.0621 ± 0.0146	0.6951	0.1884
0.05	0.9379 ± 0.0189	0.9277 ± 0.0267	0.0621 ± 0.0189	0.6996	0.1862
0.10	0.9394 ± 0.0161	0.9288 ± 0.0250	0.0606 ± 0.0161	0.7024	0.1848
0.20	0.9364 ± 0.0086	0.9266 ± 0.0175	0.0636 ± 0.0086	0.7090	0.1811
0.40	0.9333 ± 0.0063	0.9242 ± 0.0119	0.0667 ± 0.0063	0.7253	0.1719
0.80	0.9394 ± 0.0054	0.9272 ± 0.0123	0.0606 ± 0.0054	0.7611	0.1514

Table S1b Index weighting

Weighting scheme	(A_T, D_TPY, E_env, S_mat)	Accuracy	Macro-F1	Spearman ρ of D
Equal	(0.25, 0.25, 0.25, 0.25)	0.9091 ± 0.0404	0.8842 ± 0.0427	0.7845
Thermal-exposure emphasis	(0.35, 0.35, 0.15, 0.15)	0.9076 ± 0.0345	0.8832 ± 0.0373	0.7218
Environment-material emphasis	(0.15, 0.15, 0.35, 0.35)	0.9227 ± 0.0395	0.9002 ± 0.0429	0.8835
Temperature emphasis	(0.40, 0.20, 0.20, 0.20)	0.9136 ± 0.0311	0.8928 ± 0.0335	0.7378
Cumulative-exposure emphasis	(0.20, 0.40, 0.20, 0.20)	0.9121 ± 0.0350	0.8897 ± 0.0406	0.7161

Table S1c Damage-type resampling strength

ϱ	Accuracy	Macro-Recall	Macro-F1	Minimum-class recall	Ordinal MAE
0.00	0.8939 ± 0.0120	0.8738 ± 0.0200	0.8777 ± 0.0265	0.7633 ± 0.0615	n.a.
0.10	0.9000 ± 0.0136	0.8867 ± 0.0274	0.8859 ± 0.0295	0.7778 ± 0.0704	n.a.
0.15	0.8970 ± 0.0174	0.8831 ± 0.0188	0.8849 ± 0.0233	0.7826 ± 0.0604	n.a.
0.20	0.8939 ± 0.0251	0.8895 ± 0.0393	0.8843 ± 0.0368	0.8045 ± 0.0476	n.a.
0.30	0.9000 ± 0.0136	0.8963 ± 0.0183	0.8882 ± 0.0265	0.7866 ± 0.0695	n.a.
0.40	0.9121 ± 0.0205	0.9113 ± 0.0251	0.9043 ± 0.0216	0.8161 ± 0.0272	n.a.

Table S1d Damage-severity resampling strength

ϱ	Accuracy	Macro-Recall	Macro-F1	Minimum-class recall	Ordinal MAE
0.00	0.9348 ± 0.0166	0.9170 ± 0.0204	0.9196 ± 0.0191	0.8407 ± 0.0462	0.0652 ± 0.0166
0.10	0.9364 ± 0.0148	0.9171 ± 0.0210	0.9200 ± 0.0189	0.8264 ± 0.0715	0.0636 ± 0.0148
0.15	0.9409 ± 0.0136	0.9249 ± 0.0159	0.9265 ± 0.0152	0.8553 ± 0.0443	0.0591 ± 0.0136
0.20	0.9424 ± 0.0148	0.9270 ± 0.0184	0.9288 ± 0.0187	0.8716 ± 0.0410	0.0576 ± 0.0148
0.30	0.9394 ± 0.0120	0.9248 ± 0.0174	0.9245 ± 0.0171	0.8792 ± 0.0274	0.0606 ± 0.0120

0.40	0.9439 ± 0.0115	0.9347 ± 0.0100	0.9333 ± 0.0107	0.8864 ± 0.0234	0.0561 ± 0.0115

Table S2. Complete benchmark and ordinal-model comparisons.

Standard baselines used the original input variables without resampling. T3 and S4 used the complete fusion feature module and partial random over-sampling. The $\lambda = 0$ comparison used the S4 cumulative ordinal architecture and the same inputs and resampling as S4, with the consistency term disabled.

Table S2a Damage-type prediction

Model	Accuracy	Macro-Precision	Macro-Recall	Macro-F1	Kappa
MLP	0.8258 ± 0.0326	0.8237 ± 0.0238	0.7762 ± 0.0360	0.7903 ± 0.0346	0.7641 ± 0.0445
RandomForest	0.8682 ± 0.0205	0.8512 ± 0.0230	0.8526 ± 0.0303	0.8493 ± 0.0264	0.8234 ± 0.0280
ExtraTrees	0.8470 ± 0.0310	0.8264 ± 0.0370	0.8250 ± 0.0531	0.8177 ± 0.0473	0.7946 ± 0.0426
HistGradientBoosting	0.8833 ± 0.0138	0.8769 ± 0.0268	0.8647 ± 0.0218	0.8678 ± 0.0199	0.8431 ± 0.0190
XGBoost	0.8758 ± 0.0182	0.8680 ± 0.0197	0.8539 ± 0.0382	0.8577 ± 0.0278	0.8327 ± 0.0263
LightGBM	0.8712 ± 0.0178	0.8649 ± 0.0149	0.8494 ± 0.0215	0.8545 ± 0.0149	0.8266 ± 0.0249
T3	0.9258 ± 0.0155	0.9139 ± 0.0256	0.9261 ± 0.0157	0.9177 ± 0.0202	0.9010 ± 0.0203

Table S2b Damage-severity prediction

Model	Accuracy	Macro-F1	Ordinal MAE	QWK
MLP	0.8303 ± 0.0366	0.7917 ± 0.0569	0.1727 ± 0.0391	0.9142 ± 0.0201
RandomForest	0.7424 ± 0.0508	0.6966 ± 0.0617	0.2652 ± 0.0559	0.8614 ± 0.0379

ExtraTrees	0.7136 ± 0.0409	0.6765 ± 0.0447	0.3030 ± 0.0479	0.8401 ± 0.0314
HistGradientBoosting	0.7379 ± 0.0427	0.6813 ± 0.0640	0.2697 ± 0.0478	0.8603 ± 0.0359
XGBoost	0.7348 ± 0.0257	0.6722 ± 0.0359	0.2727 ± 0.0367	0.8559 ± 0.0402
LightGBM	0.7303 ± 0.0243	0.6727 ± 0.0410	0.2773 ± 0.0291	0.8554 ± 0.0292
OrdinalLogistic	0.8015 ± 0.0196	0.7781 ± 0.0326	0.2045 ± 0.0214	0.8922 ± 0.0149
Cumulative ordinal MLP	0.7379 ± 0.0532	0.6385 ± 0.1139	0.2742 ± 0.0630	0.8458 ± 0.0410
Cumulative ordinal network ($\lambda = 0$)	0.9379 ± 0.0146	0.9276 ± 0.0218	0.0621 ± 0.0146	0.9702 ± 0.0071
S4 ($\lambda = 0.80$)	0.9394 ± 0.0054	0.9272 ± 0.0123	0.0606 ± 0.0054	0.9709 ± 0.0028

Abbreviations: ROS, random over-sampling; QWK, quadratic weighted kappa.