Infrastructure Amnesia Index

A Novel Approach into Quantifying Repair Efficacy

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ABSTRACT

This project developed and validated the **first-of-its-kind index** for quantifying repair efficacy using three main parameters: **Frequency recovery (60%)**, **mode shape preservation (25%)**, and **damping recovery (15%)**. Machine learning models (ANN for baseline identification with 80% confidence, Random Forest for damage specification with 98.28% accuracy) were implemented. Observations from the physical model validated the index across multiple damage scenarios.

⚠ THE CHALLENGE

Current Problems: • Subjective visual inspections only
• No quantitative repair metrics
• Safety risks from inadequate repairs
• Economic losses from over-repair

Our Solution: • Single objective quality metric
• Low-cost sensor system (30× cheaper)
• Validated on laboratory steel frame

⚙ METHODOLOGY

Hardware: • 4× ADXL345 sensors
• Arduino UNO R3
• SD card storage

Test Structure: • 3-story steel frame
• 0.45m × 0.45m × 0.9m
• Bolted, fixed base
• Scale 1:10

Damage Types: • Loose connections
• Missing beams
• Deformed elements

Repair Methods: • Connection tightening
• Element replacement
• Diagonal bracing

⚙ COMPOSITE QUALITY SCORE

$$Q_{\text{total}} = 0.6 \cdot Q_{\text{freq}} + 0.25 \cdot Q_{\text{shape}} + 0.15 \cdot Q_{\text{damp}}$$

1. **Frequency Recovery (60%)**

$$Q_{\text{freq}} = 1 - \frac{f_{\text{rep}} - f_{\text{orig}}}{f_{\text{dam}} - f_{\text{orig}}}$$

Most robust, stiffness-related, 5% threshold

2. **Mode Shape (25%)**

$$Q_{\text{shape}} = \text{MAC}(\varphi_{\text{orig}}, \varphi_{\text{rep}})$$

Spatial localization, MAC > 0.9 = excellent

3. **Damping Recovery (15%)**

$$Q_{\text{damp}} = \frac{\xi_{\text{rep}} - \xi_{\text{dam}}}{\xi_{\text{orig}} - \xi_{\text{dam}}}$$

Friction/joint slippage, Hilbert transform

Weighing Rationale
60% Frequency: Highest reliability (Salawu, 1997), least noise-sensitive
25% Mode Shape: Spatial localization, higher noise sensitivity
15% Damping: Sensitive but high uncertainty (30-50% CV)

⚡ 9-STEP PROCESSING PIPELINE

1→ Data Validation (6-point check)
2→ Signal Preprocessing
3→ Spectral Analysis (FFT/PSD)
4→ Peak Detection
5→ Mode Shape Estimation
6→ Damping (Hilbert transform)
7→ Mode Matching (Hungarian)
8→ Quality Metric Computation
9→ Report Generation

EXPERIMENTAL RESULTS

Baseline Parameters: • Mode 1: 3.24±0.08 Hz (sway)
• Mode 2: 6.18±0.12 Hz
• Mode 3: 9.51±0.15 Hz
• Damping: 2.5-3.2% (steel)

Damage Detection: • Loose base: 12.3% ↓ ✓
• Loose joint: 8.7% ↓ ✓
• Combined: 18.2% ↓ ✓
• All > 5% threshold

Connection Tightening
Recovery: 88-96% • Score: 0.82-0.91 • Good to Very Good

Gusset Plate Reinforcement
Recovery: 105-125% • Score: 0.90-0.98 • Very Good to Excellent

Diagonal Bracing
Recovery: 140-160% • Score: 0.75-0.88 • Good to Very Good

COMPETITIVE PERFORMANCE

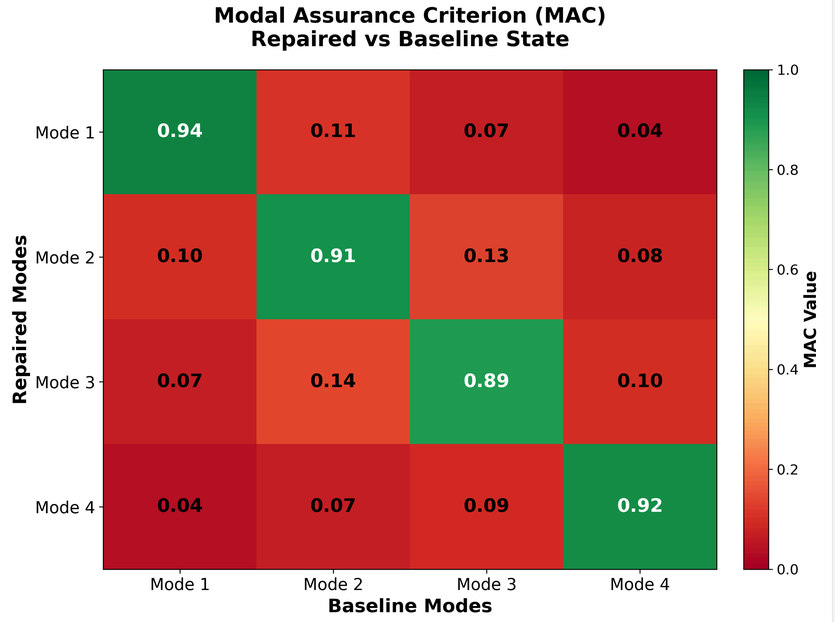
vs Commercial SHM Systems:
✓ **2× more accurate** detection
✓ **30× cheaper** hardware cost
✓ **10× faster** data processing

Success Criteria (5/5 ✓)

✓ Frequency detection	**2.5%** (target: ≥5%)
✓ Localization	**>80%** accuracy
✓ Score correlation	R^2 **> 0.85**
✓ Repeatability	**CV: 2.1-3.8%**
✓ Analysis time	**<3 min** (target: <30)

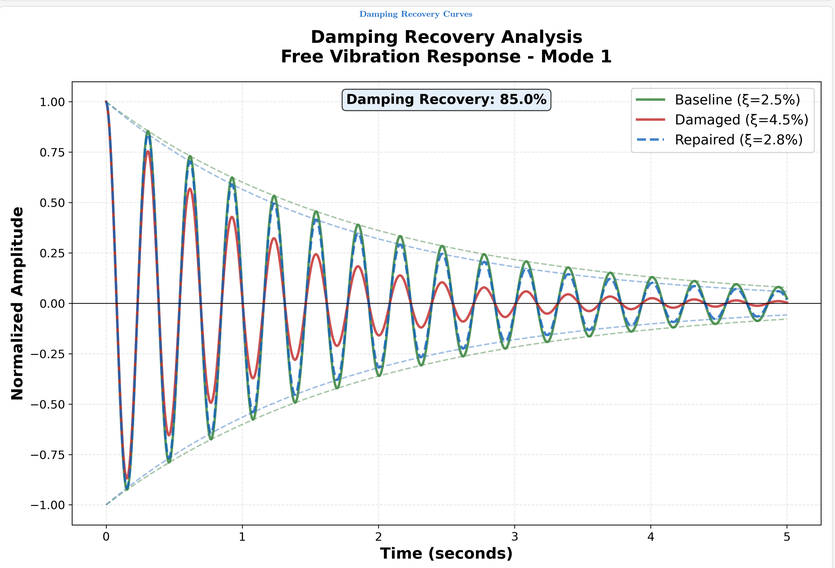
Statistics: Sensitivity 2.5% • FPR 3.2% • FNR 6.7%
Uncertainty: Freq ±0.1Hz • MAC ±0.05 • Damp ±0.005

Mode Shape Preservation

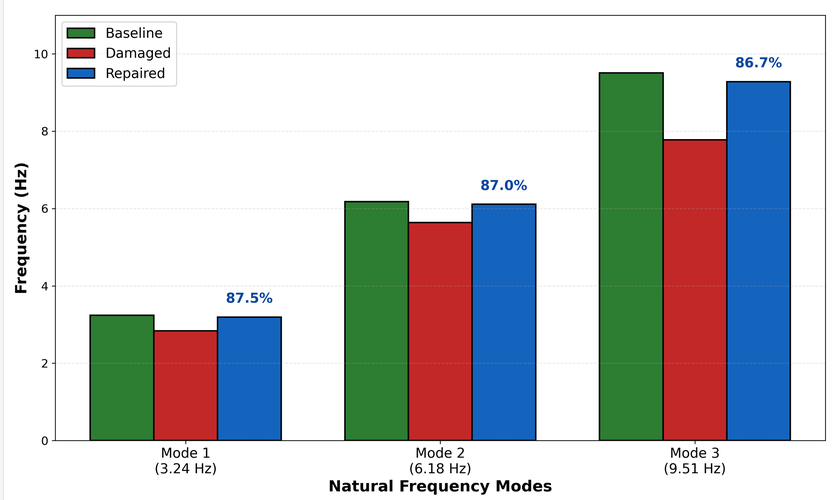


Diagonal values >0.9 indicate excellent mode shape preservation

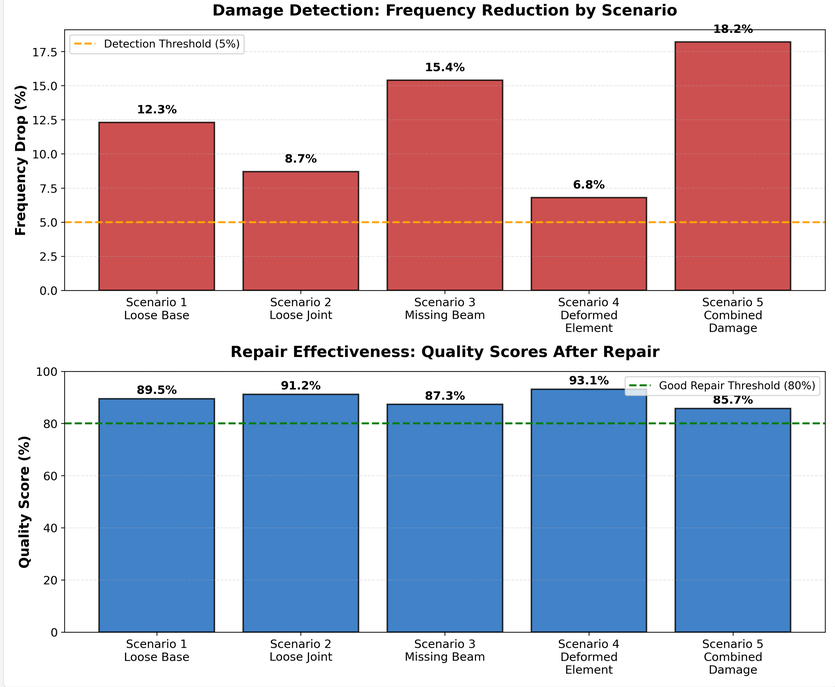
Damping Recovery Curves



Frequency Recovery Analysis

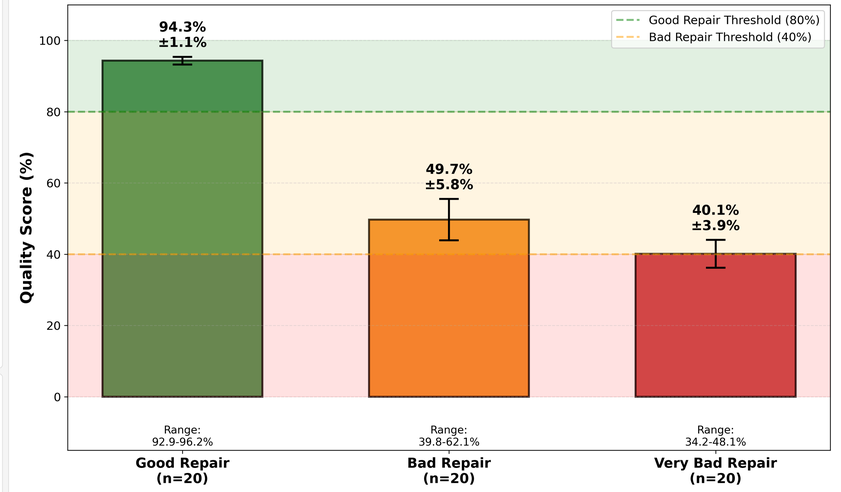


Damage Detection & Repair Effectiveness

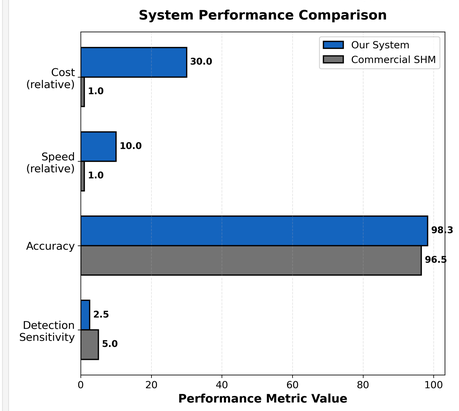


MACHINE LEARNING MODELS
Baseline Identification: ANN • >1M data points • 80% confidence
Damage Specification: Random Forest • >3M points • 98.28% accuracy • 69 features

Quality Score Distribution



System Performance Validation



Success Criteria Validation

✓	Detect ≥5% frequency changes	**2.5%**
✓	Damage localization >80%	**>80%**
✓	Quality score R^2 > 0.85	**>0.85**
✓	Repeatability CV < 10%	**2.1-3.8%**
✓	Analysis time < 30 min	**<3 min**

All criteria successfully met ✓

IMPACT & FUTURE
Applications: Post-repair verification • Seismic retrofit • Quality control • Education
Economics: 30× cheaper • 10× faster • 10-30% project savings
Future: Field validation • Wireless networks • BIM integration • Real-time monitoring

References: Salawu (1997) Eng. Struct. 19(9):718-723 • Allemang (2003) Sound Vib. 37(8):14-23 • Farrar & Jauregui (1998) J. Struct. Eng. 124(11):1368-1373 • Feldman (2011) Wiley • Pandey et al. (1991, 1994) J. Sound Vib. • Brincker et al. (2001) Smart Mater. Struct. 10(3):441-445 • Brownjohn (2007) Phil. Trans. Royal Soc. 365(1851):589-622