INDIA CHAPTER

IRF INTERNATIONAL ROAD FEDERATION

Global Road Infratech Summit & Expo

05-06 FEBRUARY 2026

GRIS GLOBAL ROAD INFRATECH SUMMIT & EXPO 2026

"Vision Zero India: Integrating Safety, Sustainability and Technology in Infra"

PROGRESSIVE DAMAGE MONITORING IN CONCRETE UNDER MONOTONIC LOADING USING AN INTEGRATED ACOUSTIC EMISSION-PIEZOELECTRIC FRAMEWORK

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Presented By
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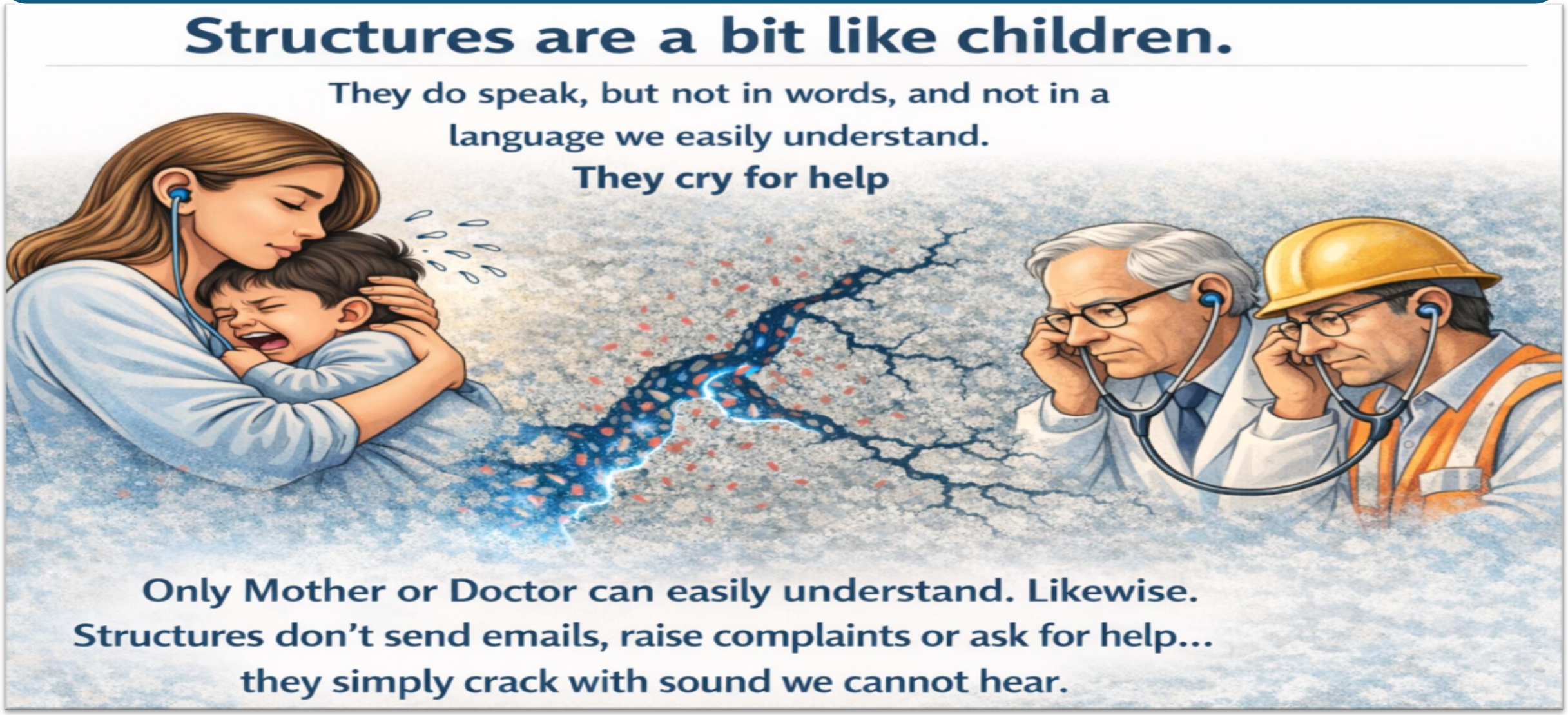
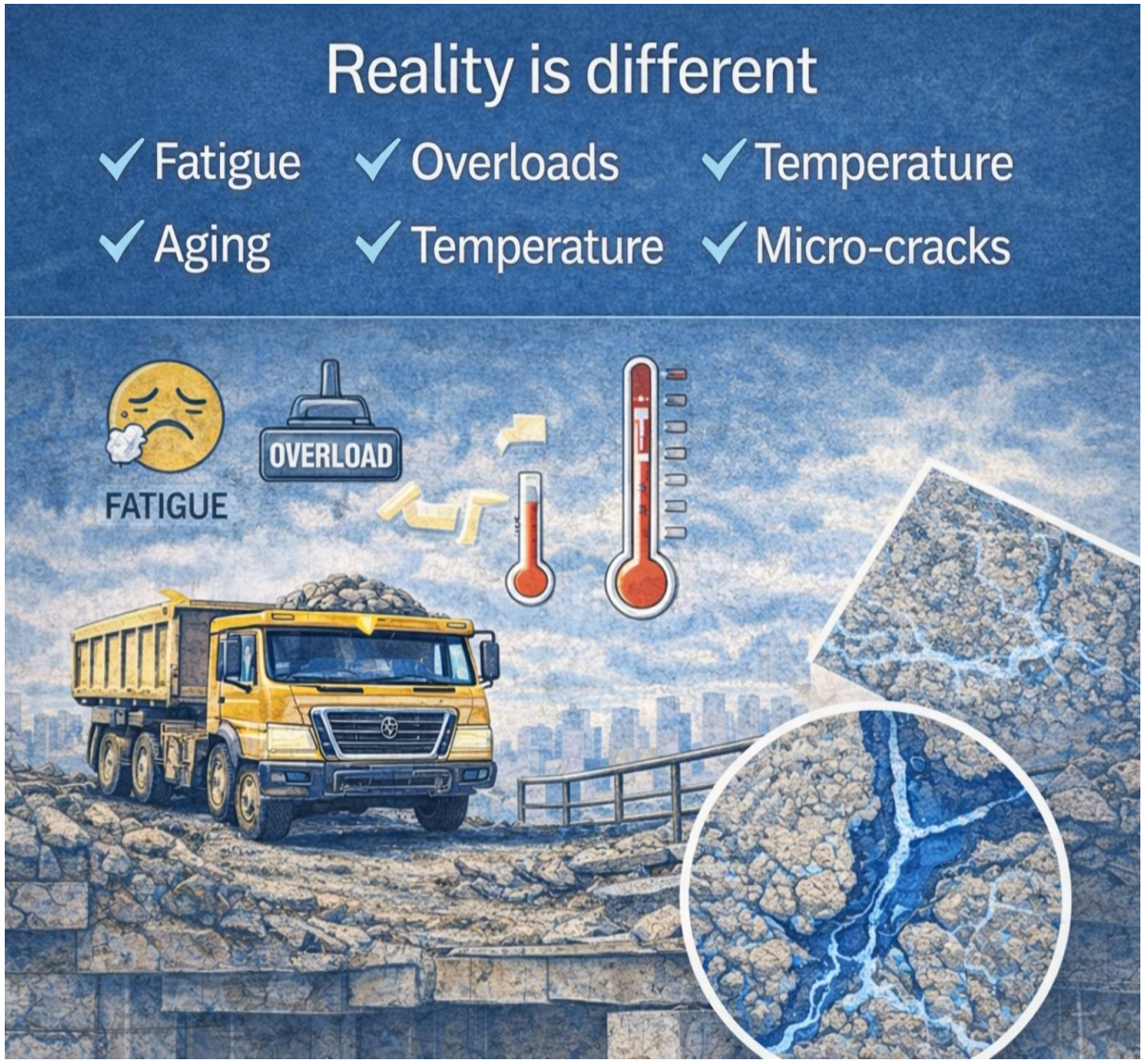
DECODING THE SILENT CRY OF STRUCTURES



RATIONALE FOR SHM IN BRIDGES



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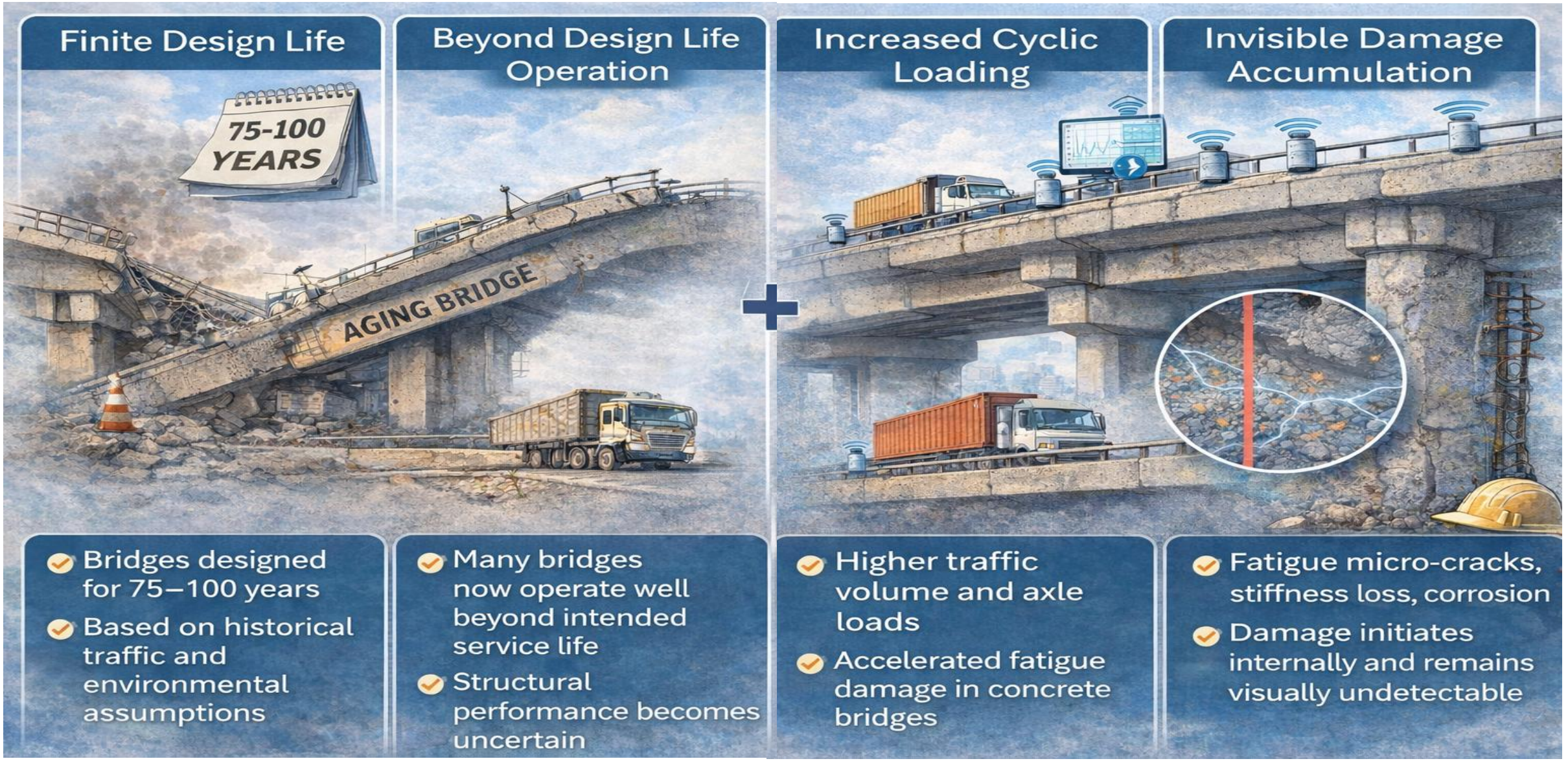
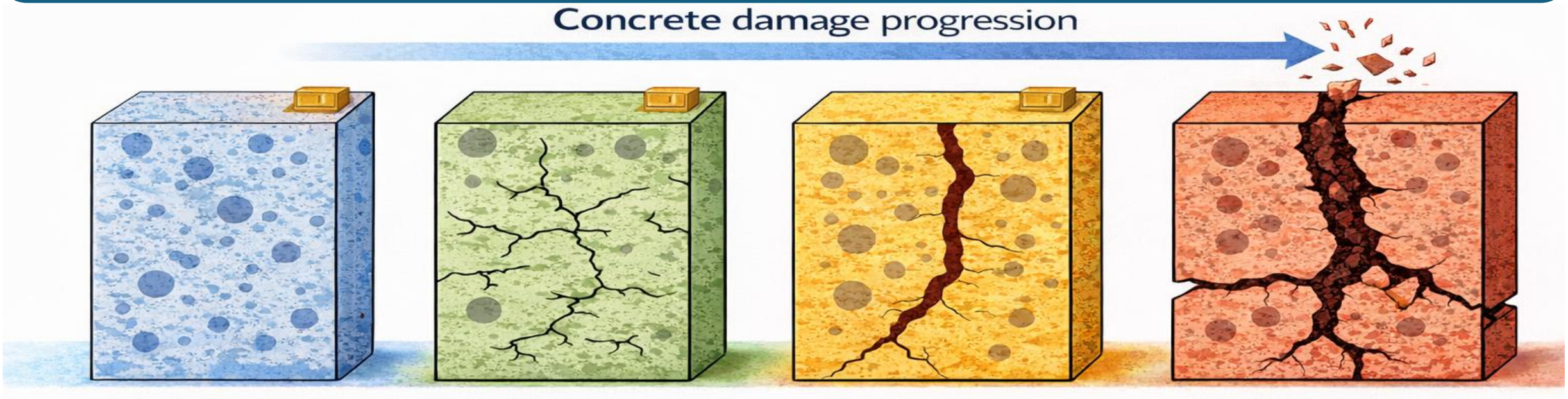


CONTEXT AND MOTIVATION

This shift from post-failure inspection to early diagnosis is the core motivation behind SHM

DAMAGE PROGRESSION IN CONCRETE



MICRO- DAMAGE	STABLE GROWTH	LOCALIZATION	UNSTABLE FAILURE
• NUCLEATION OF MICRO CRACKS • STIFFNESS - INTACT • DIFFUSE CRACKING	• INTERCONNECTION OF FINER CRACKS • GRADUAL STIFFNESS REDUCTION • FATIGUE CRACK GROWTH	• COALESCENCE IN TO PRIMARY CRACK • RAPID STIFFNESS REDUCTION • RAPID WIDENING CRACK	• GROWTH OF PRIMARY CRACK • SEVERE STIFFNESS REDUCTION • FORMATION OF MACRO CRACK

CONVENTIONAL IN SHM METHODS

METHOD / SENSOR	WORKS FOR	SENSITIVITY RANGE
UPV (Ultrasonic Pulse Velocity)	Uniformity & internal flaws	Averages response; insensitive to microcracks in early stage
Rebound Hammer	Surface hardness	Surface-only, poor correlation to micro-damage
Radiography (X-ray)	Void / crack detection	Expensive, safety issues, limited field use
Infrared Thermography	Debonding, moisture	Surface-thermal only, not crack-sensitive deep inside
Vibration-based Monitoring	Global stiffness, mode shapes	Detects late-stage damage only -global response masking local cracks
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Strain Gauges / LVDTs	Local deformation & strain	Point-based, cannot detect crack initiation; wires & installation issues
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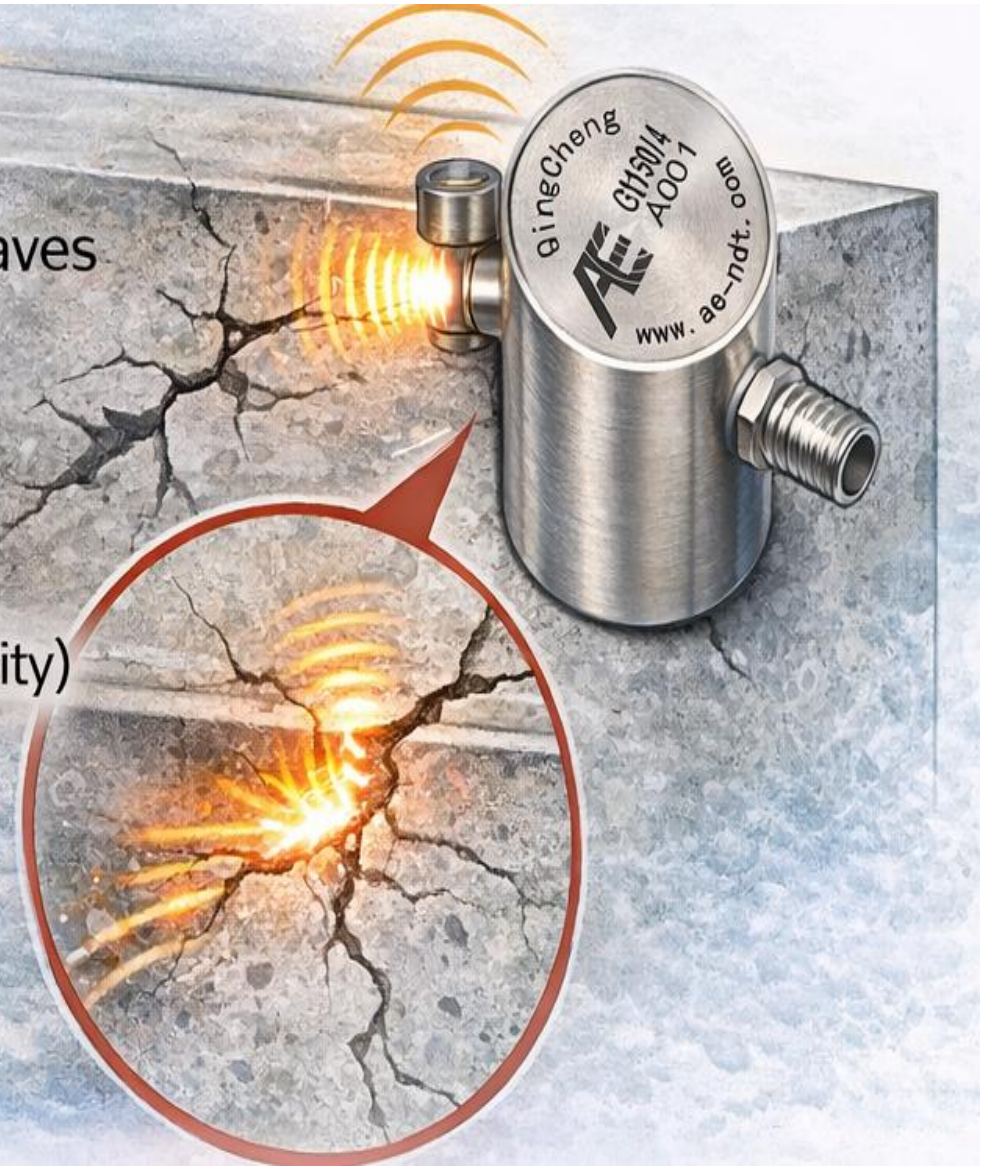
……CONVENTIONAL IN SHM METHODS

METHOD / SENSOR	WORKS FOR	SENSITIVITY RANGE
Fiber Optic Sensors (FBG)	Strain, temperature, distributed sensing	Needs embedding or surface bonding, costly, limited crack sensitivity
DIC (Digital Image Correlation)	Full-field strain visualization	Camera-based, requires clear access, not continuous, lighting sensitive
Ground Penetrating Radar (GPR)	Voids, rebar mapping	Difficult interpretation, weak for fine cracks
Corrosion Sensors & Half-Cell Potential	Steel corrosion monitoring	Damage already initiated; not crack-focused
Corrosion Sensors & Half-Cell Potential	Steel corrosion	Damage already initiated; not crack-focused
Visual Inspection / Hammer Tap	Surface defects	Subjective, detects only visible macro-damage

By the time most conventional methods detect damage, cracking has already progressed too far to prevent deterioration.

ACOUSTIC EMISSION WAVE SENSOR

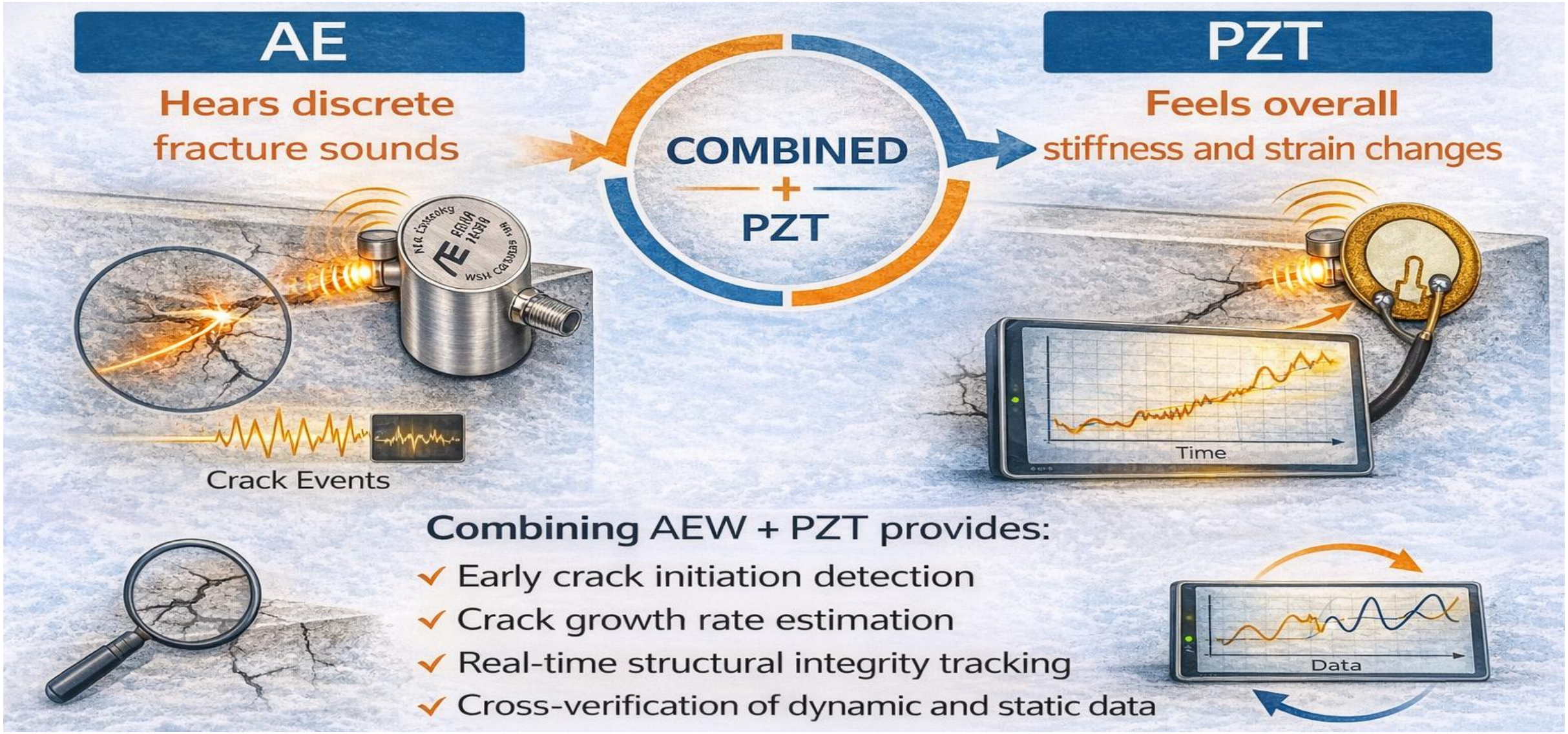
- It “listens” to tiny sound waves generated inside concrete when microcracks form.
- Every small crack emits a *burst of elastic stress* waves that travel through the concrete.
- AE captures:
  - ✓ **Amplitude (Vmax)** – how strong the burst is.
  - ✓ **Counts** – how many threshold crossings (crack activity)
  - ✓ **Energy** – total intensity of the wave
  - ✓ **Frequency** – relates to crack type (tensile or shear)
- AE gives you *instantaneous* crack events — like a **seismograph for concrete.**



PZT (PIEZOELECTRIC) SENSOR

- ✔ **Behaves like a smart strain gauge.**
- ✔ **When concrete deforms, the PZT patch experiences mechanical strain and produces a small voltage.**
- ✔ **Sensitive to *cumulative stiffness* changes** (gradual weakening).

AEW AND PZT SENSORS



IS AE–PZT Fusion NEW??

Sl. No	Case Study	Details
1	**Real-Time Monitoring of a Concrete Bri Ser** pat **Pro** To cor	AE detected **first microcrack events** even before visible
2	**Loa (Ind Ser** bor **To** deg	
3	**Wi (De Ser** + P **To** larg	

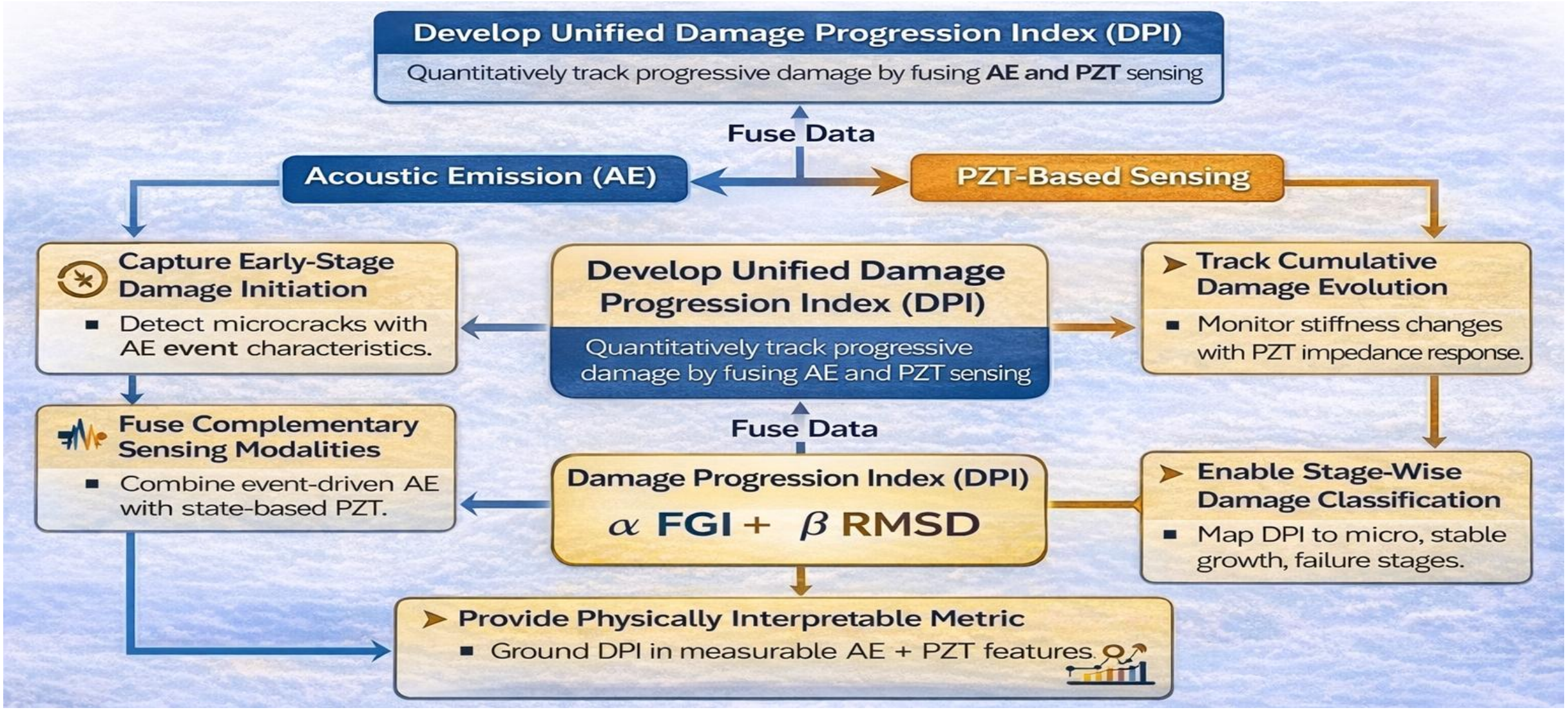
Sl.No	Case Study	Details
4	**Aircraft Wing Panel Monitoring (Airbus Research Pr Sensors use distributed F To Detect im cracks in ca**	AE identified impact events milliseconds after they occurred
5	**Corrosion D (Saudi Aram Sensors use activity + PZ To Detect co buried oil pi**	
6	**Cable-Staye (China – Sut Sensors use**	

Sl. No	Case Study	Details
7	**Precast Concrete Tunnel Segment Monitoring (Singapore MRT)** **Sensors used: Embedded PZT patches + AE surface sensors** **To Detect microcracking during heavy construction loads.**	AE detected early cracking from segment handling. PZT identified changes in structural modulus from long-term creep. Fusion helped ensure segment integrity before underground installation.
8	**Composite Armor Panel Testing (DRDO – India)** **Sensors used: AE + PZT** **To Track damage from ballistic impacts and subsequent loading.**	AE detected fiber rupture events during impact. PZT mapped hidden subsurface delamination that AE alone couldn't reveal. Fusion provided a complete picture of the panel's survivability.
9	**3D-Printed Concrete Wall Monitoring (Europe – Eindhoven University)**	AE detected layer debonding between printed layers. PZT measured progressive stiffness loss due to micro void

IDENTIFIED RESEARCH GAP

Sl. No	Description	Research Gap
1	**Predominantly Parallel, Not Fused, Use** ▪ AE is mainly used for **passive damage detection** (crack initiation, energy release). ▪ PZT-guided ultrasonic waves are used for **active interrogation** (damage localization, stiffness change).	Lack of frameworks that **jointly exploit AE + PZT signals** in a **unified fusion model** rather than side-by-side interpretation.
2	**Limited Multi-Level Fusion Strategies** ▪ Sensor-level deployment challenges ▪ Signal interpretation independently ▪ Multi-PZT fusion with ML	Absence of **systematic fusion approaches,** such as: ▪ Signal-level fusion (shared feature spaces). ▪ Feature-level fusion (AE energy, counts + PZT wave velocity, attenuation) ▪ Decision-level fusion (combined damage indices)
3	**Lack of AE-PZT Fusion with Machine Learning** ▪ ML is applied mainly to **multi-PZT systems,** not heterogeneous AE + PZT data. ▪ AE signals are often excluded due to their stochastic nature.	No robust ML or AI models that: ▪ Handle different **sampling rates, bandwidths,** and **physics** ▪ Learn correlated **damage signatures** from AE.

OBJECTIVE


Develop Unified Damage Progression Index (DPI)
Quantitatively track progressive damage by fusing AE and PZT sensing
Fuse Data
Acoustic Emission (AE)
PZT-Based Sensing
Capture Early-Stage Damage Initiation
Detect microcracks with AE event characteristics.
Develop Unified Damage Progression Index (DPI)
Quantitatively track progressive damage by fusing AE and PZT sensing
Track Cumulative Damage Evolution
Monitor stiffness changes with PZT impedance response.
Fuse Complementary Sensing Modalities
Combine event-driven AE with state-based PZT.
Fuse Data
Damage Progression Index (DPI)
α FGI + β RMSD
Enable Stage-Wise Damage Classification
Map DPI to micro, stable growth, failure stages.
Provide Physically Interpretable Metric
Ground DPI in measurable AE + PZT features.

EXPERIMENTAL STUDY

AE sensor: GL150 (~150 kHz), Preamp +40 dB

PZT: 20 mm disc, 10–200 kHz bandwidth

Oscilloscope:

1 GS/s, USB data export to CSV

EXPERIMENTAL STUDY

Specimen Details

- M30 concrete cubes (150×150×150 mm).
- Standard curing (28 days).

Loading Protocol

- Monotonic compression at 5.20 kN/s until failure.
- Load & displacement recorded.

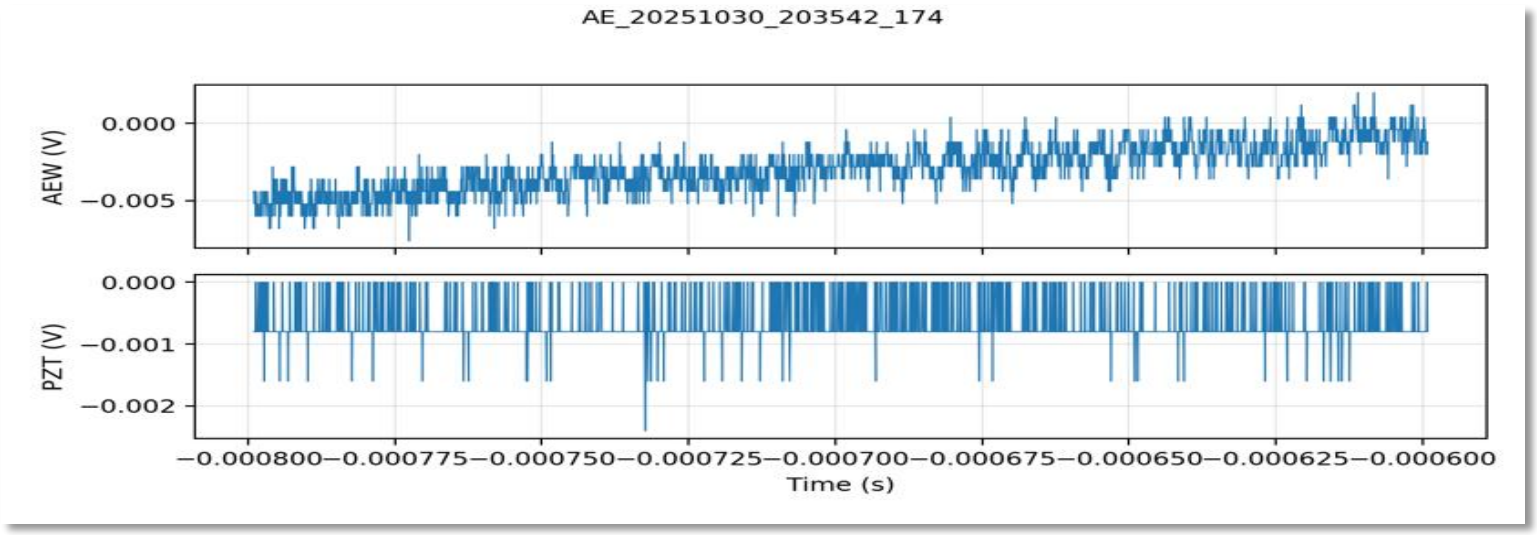
Sensors & Mounting

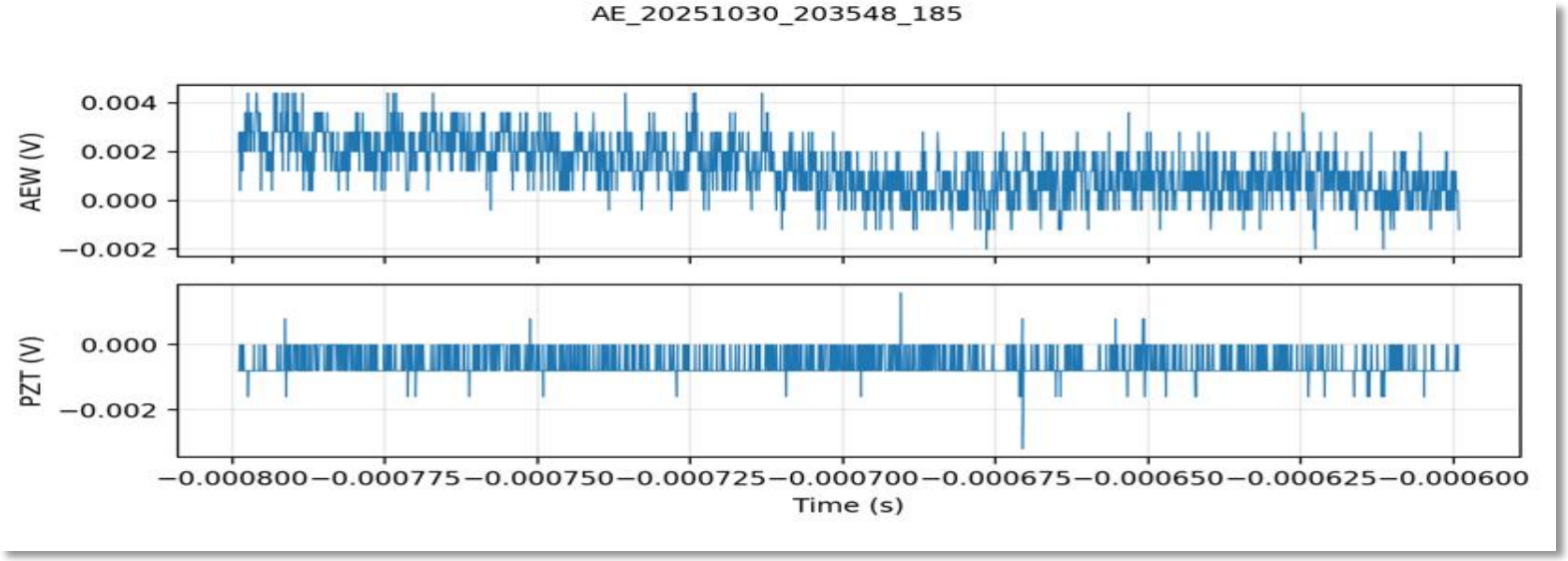
- AEW GL150 (100–400 kHz) and
- PZT discs bonded with grease coupling.

Data Acquisition

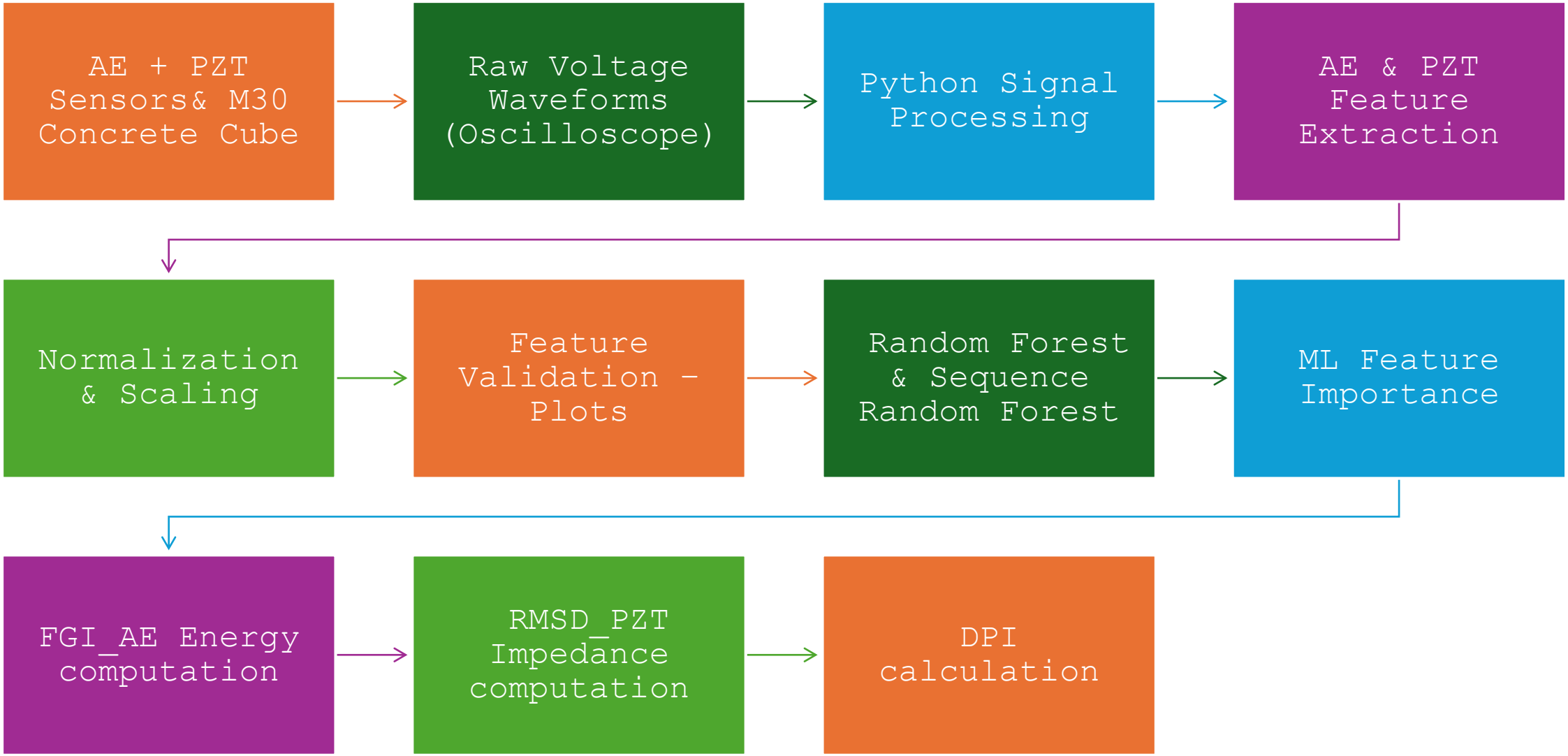
- Mixed-domain oscilloscope, 2.5 MHz sampling.
- Channels: Ch1=AE, Ch2=PZT; saved to CSV/MAT.

RAW SIGNAL FROM SENSORS





METHODOLOGY



AE FEATURE EXTRACTION - PYTHON

Acoustic Emission (AE) – Time Domain Features

Feature	Definition	Physical Meaning
AE_Vmax	max(v)	AE voltage
AE_RMS	√mean(v²)	Average AE signal strength
AE_Energy	∑ v²	Total AE energy released (damage activity)

Acoustic Emission (AE) – Frequency Domain Features

Feature	Definition	Physical Meaning
AE_PeakF	Frequency of max FFT magnitude	Dominant AE source frequency
AE_AvgF	Weighted mean frequency	Overall spectral balance
AE_CentroidF	Spectral centroid	Shift toward high/low-frequency damage modes

Acoustic Emission (AE) – Damage Statistics

Feature	Definition	Physical Meaning
AE_bValue	-slope of log(N) vs log(A)	Crack mode indicator (macrocracking)
AE_bIntercept	Regression intercept	AE population scaling
AE_CumEnergy	Cumulative AE energy	Damage accumulation
AE_FGI	Normalized cumulative AE energy (0–1)	**Failure Growth Index** (damage progression)

PZT FEATURE EXTRACTION - PYTHON

Piezoelectric Sensor (PZT)– Time Domain Features

Feature	Definition	Physical Meaning
PZT_Vmax	max(	PZT voltage
PZT_RMS	√mean(v²)	Global vibration level
PZT_Energy	∑ v²	Global response energy

PZT – Impedance-Based Damage Proxies

Feature	Definition	Physical Meaning
PZT_Impedance	Energy / RMS	EMI-based stiffness proxy
PZT_MechImpedance	1 / PZT _Impedance	Mechanical impedance (inverse stiffness)

AE-PZT FEATURE EXTRACTION:PYTHON

AE–PZT Coupling Features

Feature	Definition	Physical Meaning
Lag_samples	Cross-correlation lag (samples)	Time delay AE PZT
Lag_s	Lag in seconds	Wave propagation / coupling delay
CrossCorrCoeff	Max normalized correlation	Strength of AE–PZT coupling

Key Feature Groups (High Diagnostic Value)

Damage initiation & growth

1. AE_Energy
2. AE_CumEnergy
3. AE_FGI
4. AE_bValue

Stiffness degradation

1. PZT_Impedance
2. PZT_MechImpedance
3. PZT_CentroidF

Local–global coupling

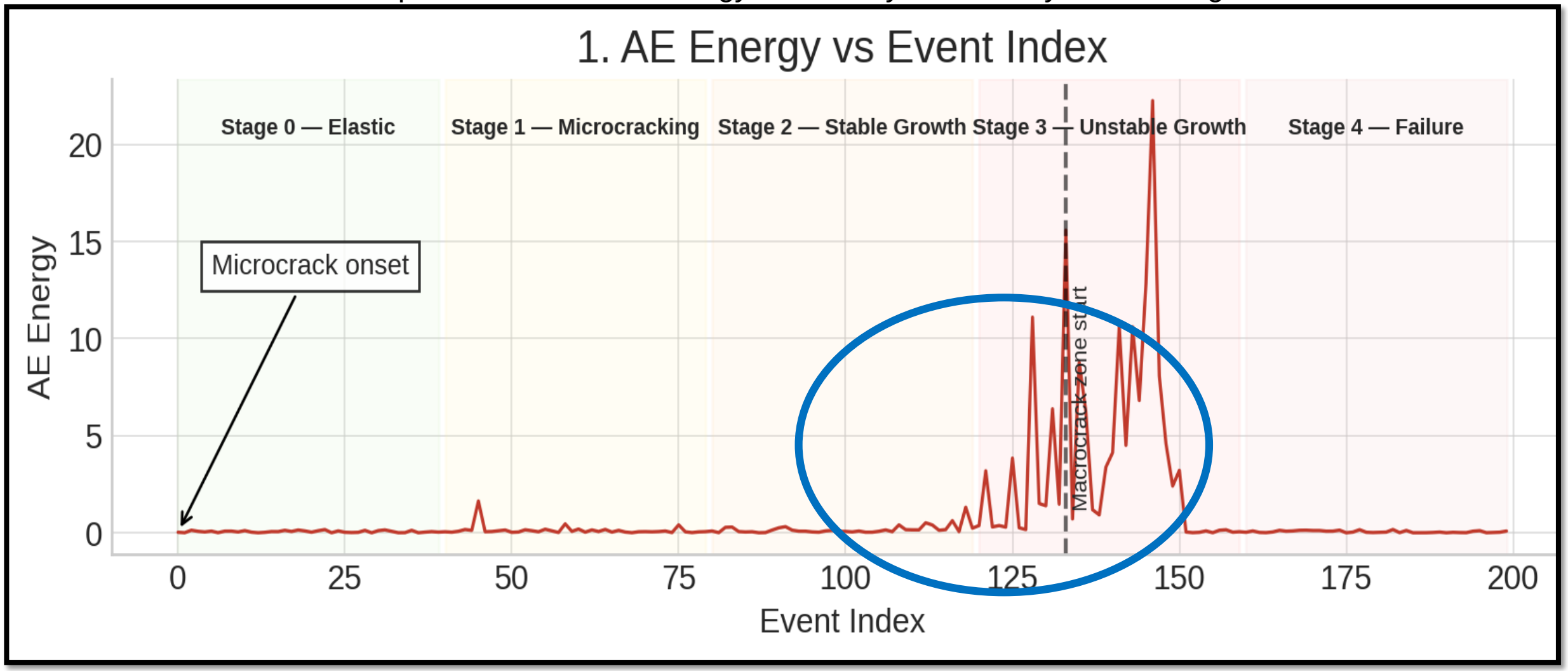
1. AE_Energy-- PZT_Energy
2. AE_Vmax -- PZT_RMS
3. CrossCorrCoeff, Lag_s

DAMAGE DETECTION AND MONITORING FRAMEWORK

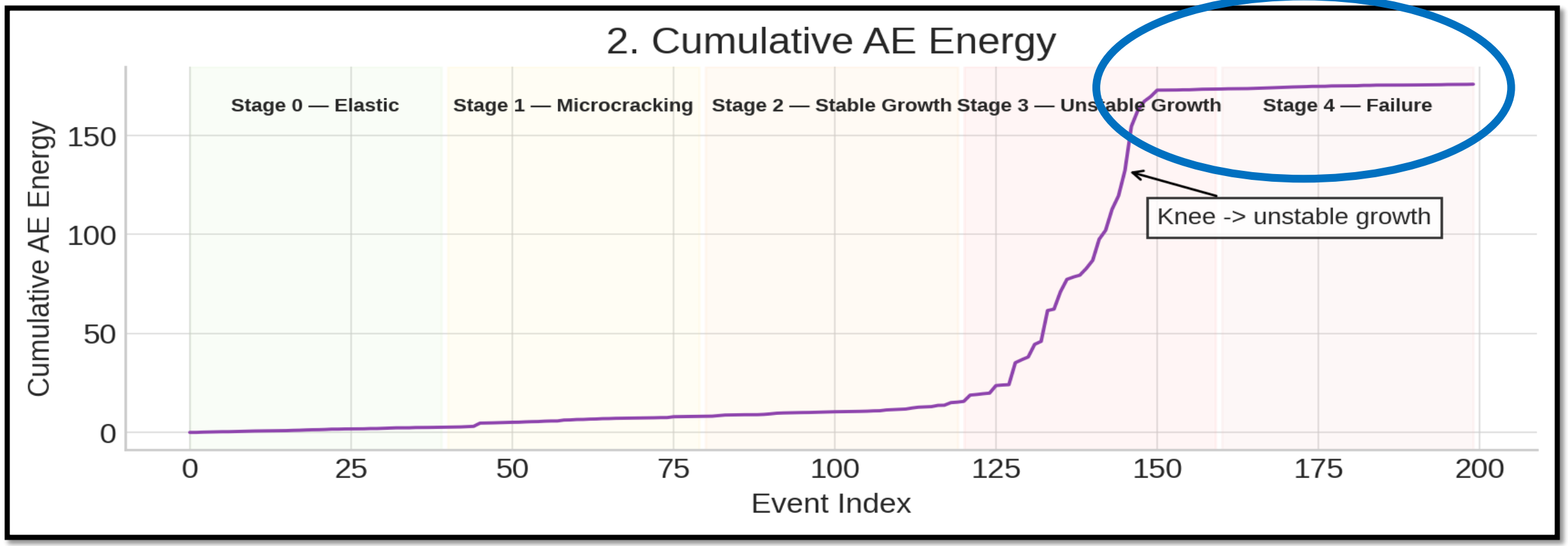
Group 1 - Damage Detection	Group 2 – Sensor Fusion Validation	Group 3 – Machine Learning Validation	Group 4 – SHM Intelligence & Prognosis
• Is damage happening? • AE energy, cumulative AE, PZT response, and fused damage index together confirm damage initiation, irreversibility, and standardized damage stages. • Plots 1-4	• Do AE and PZT observe the same damage? • Dual-axis, frequency, impedance, lag, and energy-coupling analyses prove simultaneous and physically consistent AE–PZT response to cracking. • Plots 6 to 11	• Can damage assessment be automated? • Confusion matrix, feature importance, sequence accuracy, and GridSearch demonstrate reliable, robust, and scalable damage classification. • Plots 12 to 15	• Can failure be anticipated? Impedance trends, b-value, frequency shifts, clustering, and thresholds enable early warning, degradation tracking, and failure prediction. • Plots 16 to 20

G1 PLOTS - EARLY FAILURE PREDICTION

This plot shows that AE energy evolves systematically with damage

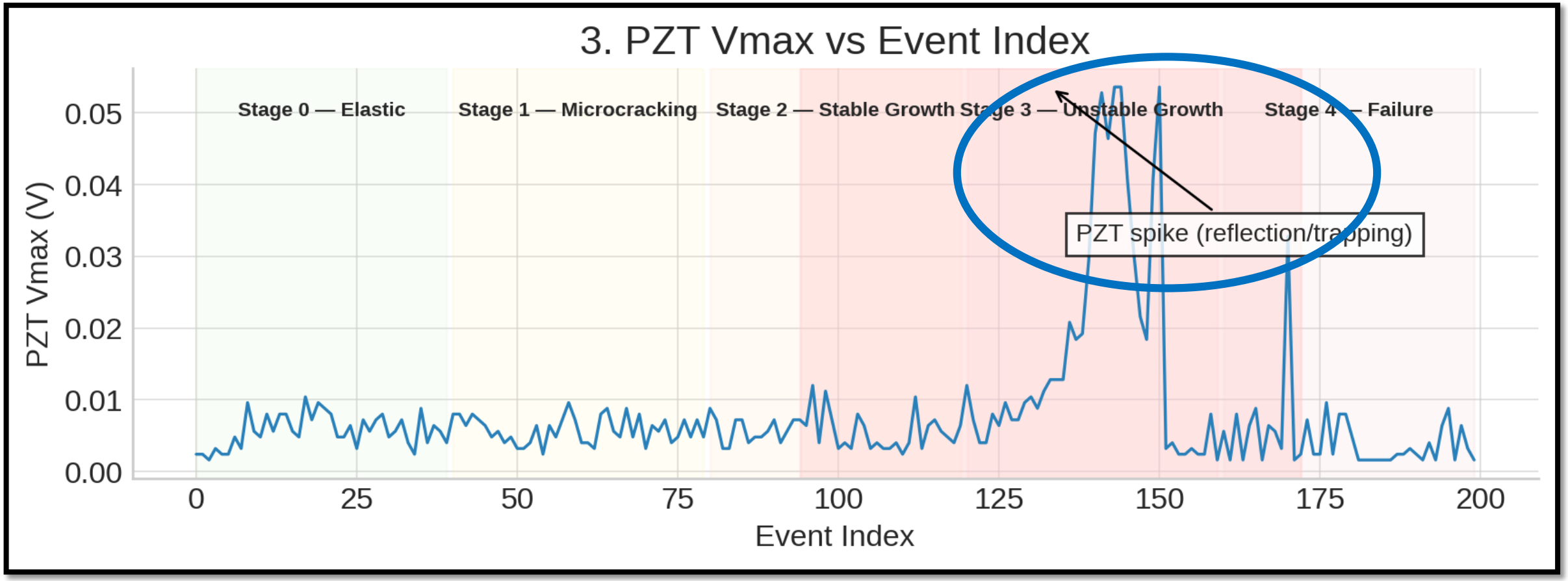


G1 PLOTS - CUMULATIVE AE ENERGY



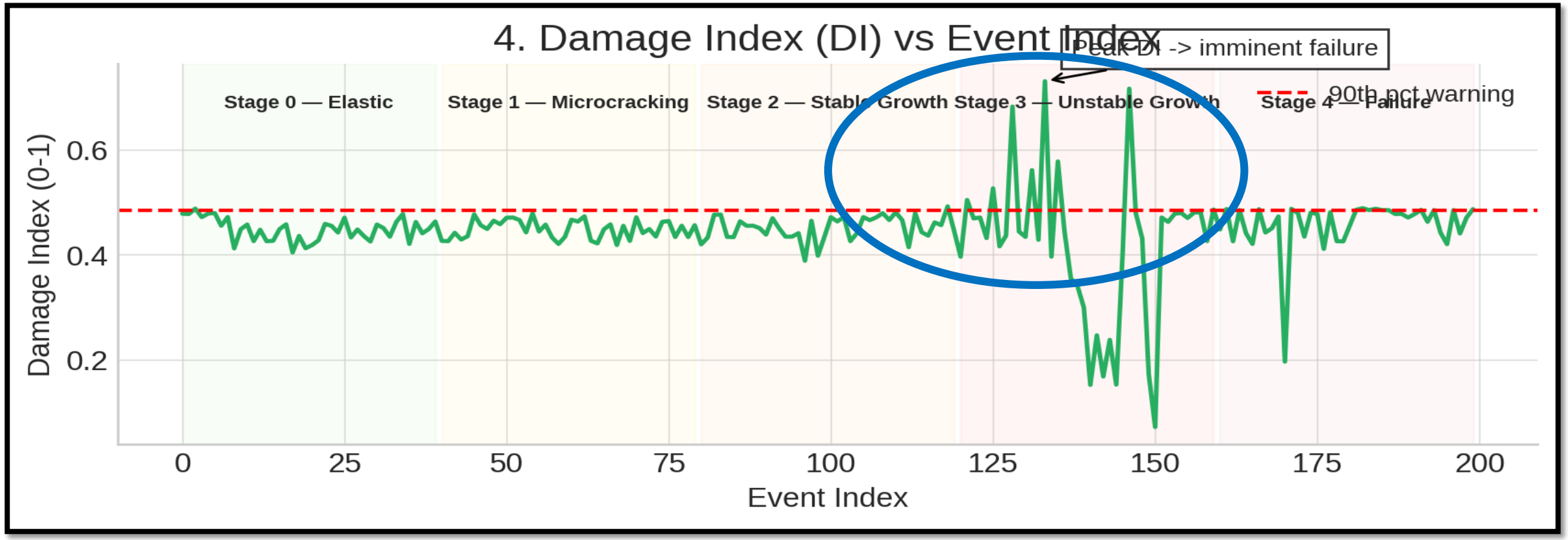
1. The cumulative AE energy curve integrates all fracture activity; its knee marks the transition to unstable crack growth.
2. The cumulative AE energy curve does not decrease after the peak because it represents the irreversible accumulation of fracture-related energy. Even after macrocrack formation, previously released energy remains in the cumulative measure, resulting in a plateau rather than a decline. This monotonic behaviour makes cumulative AE energy a robust indicator for progressive damage and failure threshold identification

G1 PLOTS - PZT VMAX Vs EVENT INDEX



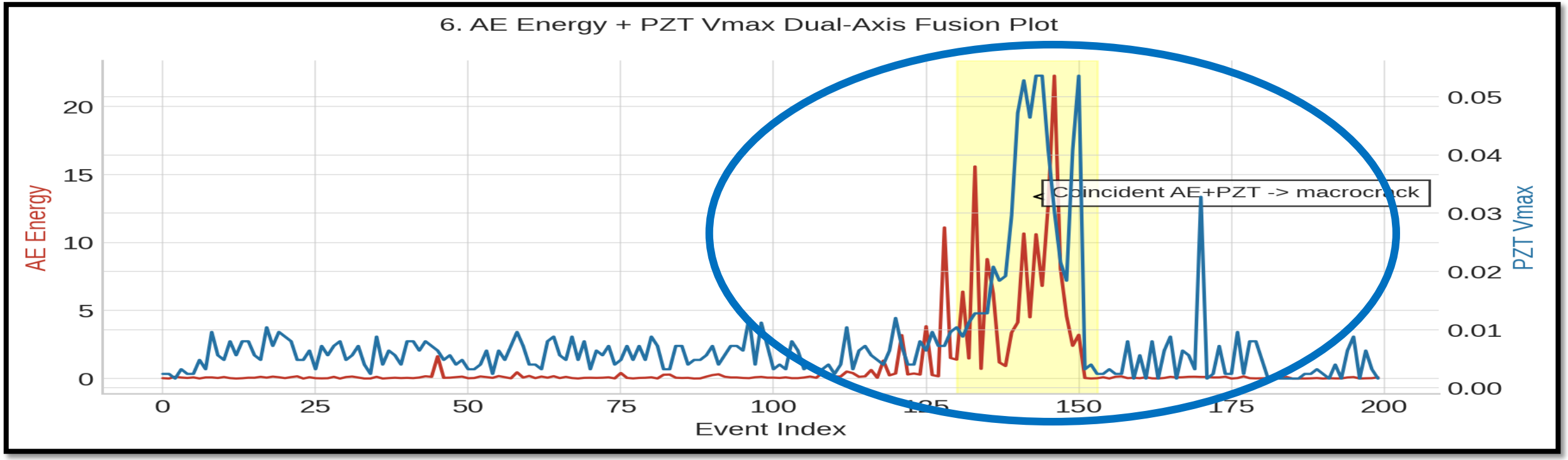
The PZT Vmax plot reveals progressive stiffness degradation during early loading and a pronounced amplitude spike during unstable crack growth. This spike, attributed to wave reflection and trapping at newly formed macrocrack surfaces, marks the onset of structural failure. The observation contradicts the conventional assumption of monotonic amplitude decay and provides a novel insight into guided-wave behavior in cracked concrete. When fused with AE data, this feature significantly enhances damage stage identification and failure prediction.

G1 PLOTS - DAMAGE INDEX (DI) Vs EVENT INDEX



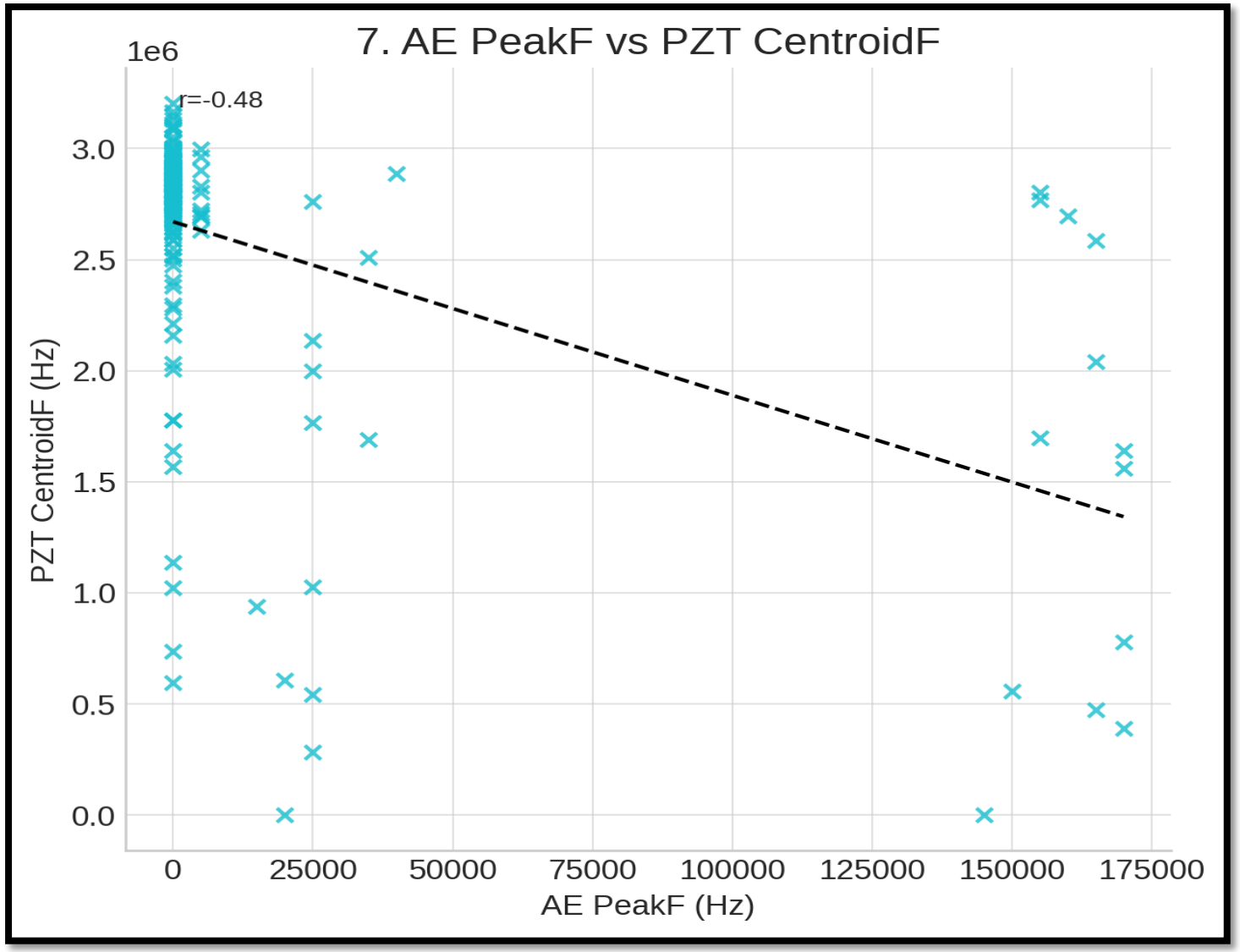
1. DI provides a single, interpretable damage metric.
2. Crossing the 90th-percentile line is a reliable early-warning signal.
3. DI peak precedes visible failure, enabling preventive action.
4. The Damage Index fuses AE and PZT information into a single normalized metric; its sharp rise and threshold crossing identify unstable crack growth and provide an early warning of imminent failure.”

G2 PLOTS - AE ENERGY + PZT VMAX DUAL-AXIS



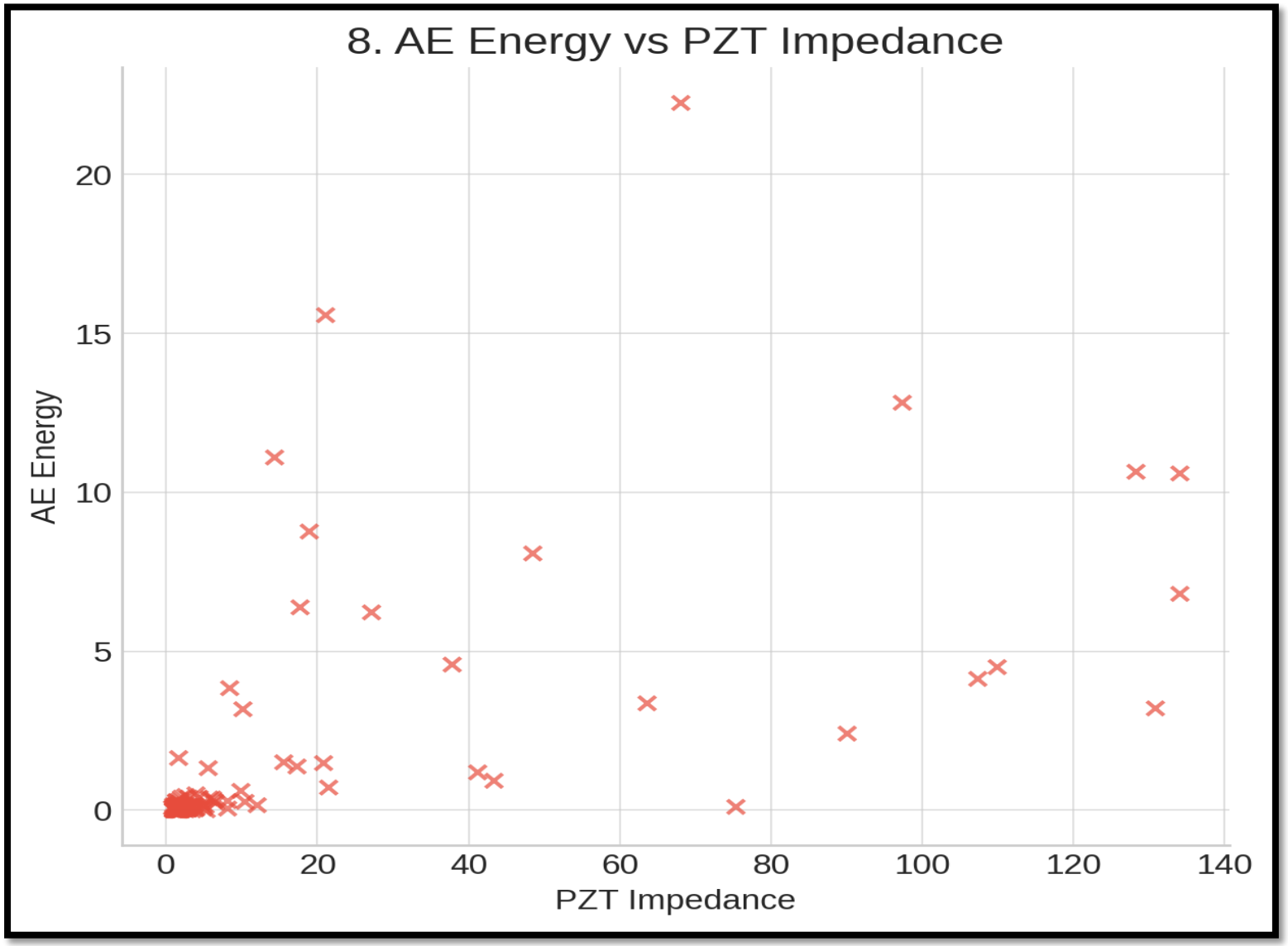
1. AE shows energy release
2. PZT shows wave interaction with crack
3. Their coincidence proves same crack, same moment
4. This is why AE–PZT fusion is superior to AE+ strain, AE+DIC, or PZT-only methods for concrete.
5. The dual-axis AE–PZT fusion plot demonstrates a clear coincident response of fracture energy release and guided-wave amplitude during unstable crack growth. The simultaneous spikes in AE energy and PZT Vmax confirm the initiation of a dominant macrocrack, providing unambiguous evidence of failure onset. This coincidence-based fusion significantly improves damage stage identification and eliminates false alarms associated with single-sensor monitoring

G2 PLOTS - AE PEAK FREQUENCY Vs PZT CENTROID FREQUENCY



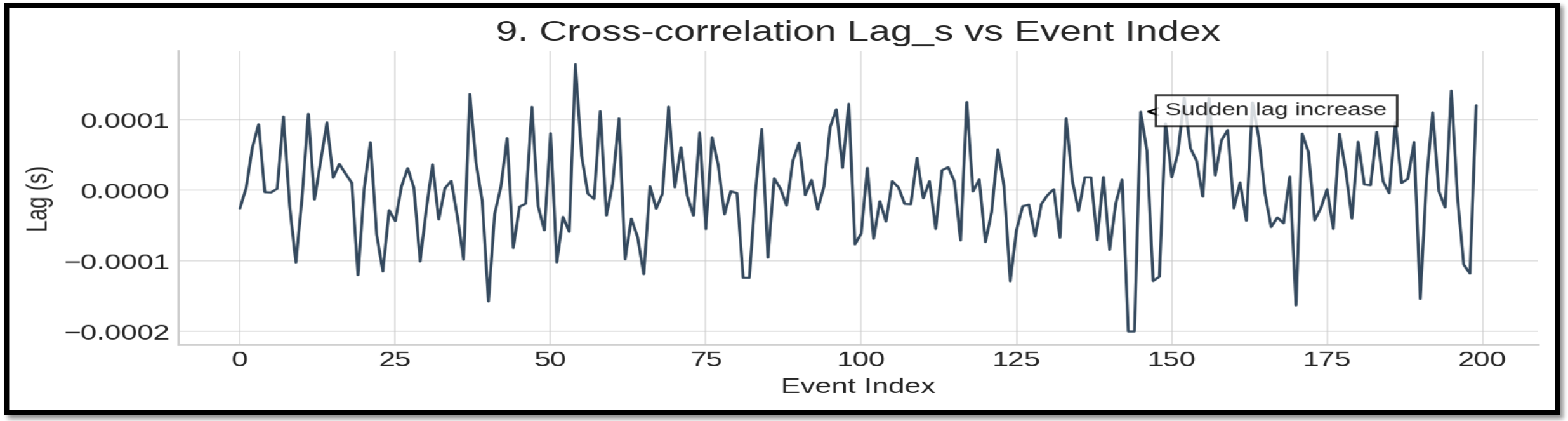
1. Confirms wave-physics consistency across sensors.
2. Demonstrates that frequency-based features carry damage information, not just amplitudes.
3. Strengthens the argument that AE–PZT fusion captures multi-scale damage mechanics
4. The negative correlation between AE peak frequency and PZT centroid frequency demonstrates that increasing damage in concrete leads to a systematic downshift in wave frequency content across both passive and active sensing modalities. This behavior is attributed to crack-induced scattering, dispersion, and increasing fracture scale. The result confirms that frequency-based features provide complementary and physically meaningful indicators of progressive damage, enhancing the robustness of AE–PZT fusion for damage stage identification

G2 PLOTS - AE ENERGY Vs PZT IMPEDANCE



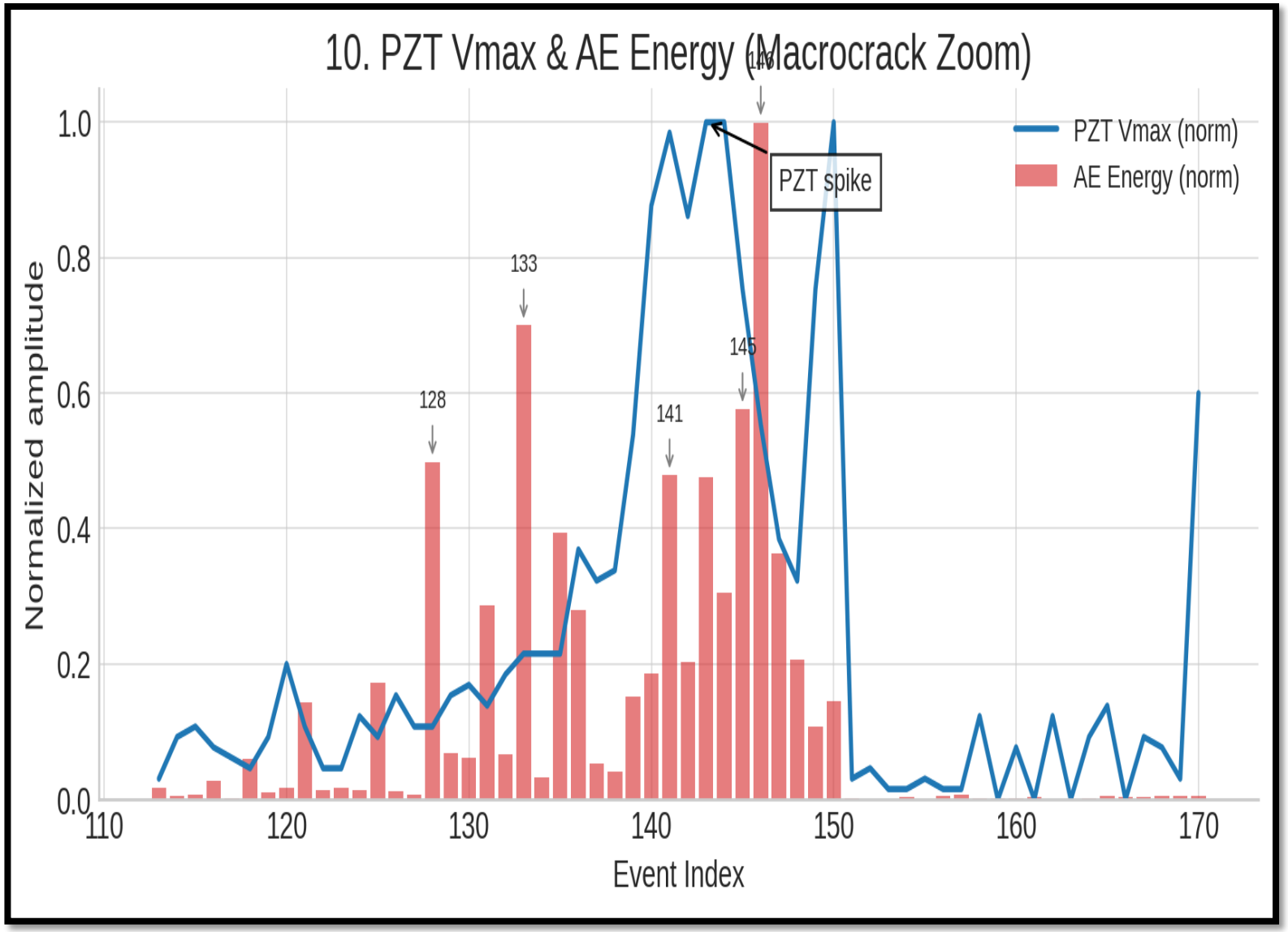
1. The scatter relationship between AE energy and PZT impedance demonstrates that progressive fracture activity in concrete leads to increasing stiffness degradation.
2. Low-energy AE events correspond to minor impedance changes during early damage stages, while high-energy AE bursts coincide with large impedance deviations associated with unstable crack growth and macrocrack formation.
3. The nonlinear scatter reflects the heterogeneous nature of concrete and confirms the complementary roles of AE and PZT sensing in capturing both local fracture events and global structural response.

G2 PLOTS - CROSS-CORRELATION LAG(S) Vs EVENT INDEX



Lag directly reflects internal geometry changes
It is sensitive to crack localization, not just crack count
It provides early confirmation of unstable crack growth
The cross-correlation lag remains near zero during elastic and stable damage stages, indicating minimal wave-path alteration. A sudden increase in lag marks the onset of unstable crack growth, reflecting significant internal path disruption due to crack coalescence. The subsequent erratic lag behavior corresponds to loss of coherent wave transmission after macrocrack formation. This confirms that cross-correlation lag is a sensitive and reliable indicator of critical damage transition in concrete.

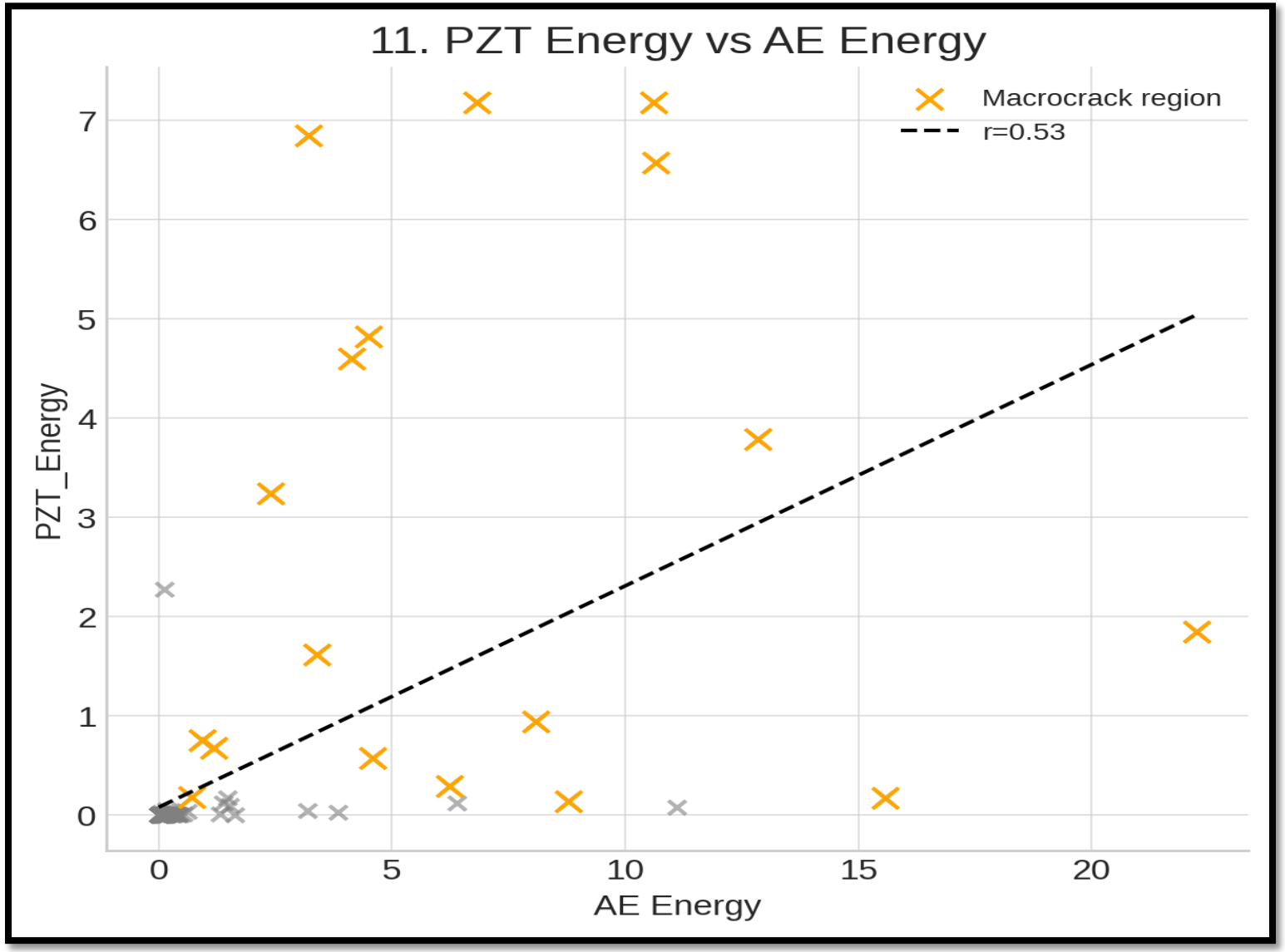
G2 PLOTS - PZT VMAX & AE ENERGY AT MACROCRACK



AE captures fracture mechanics
PZT captures wave–crack interaction
Their coincidence captures failure physics

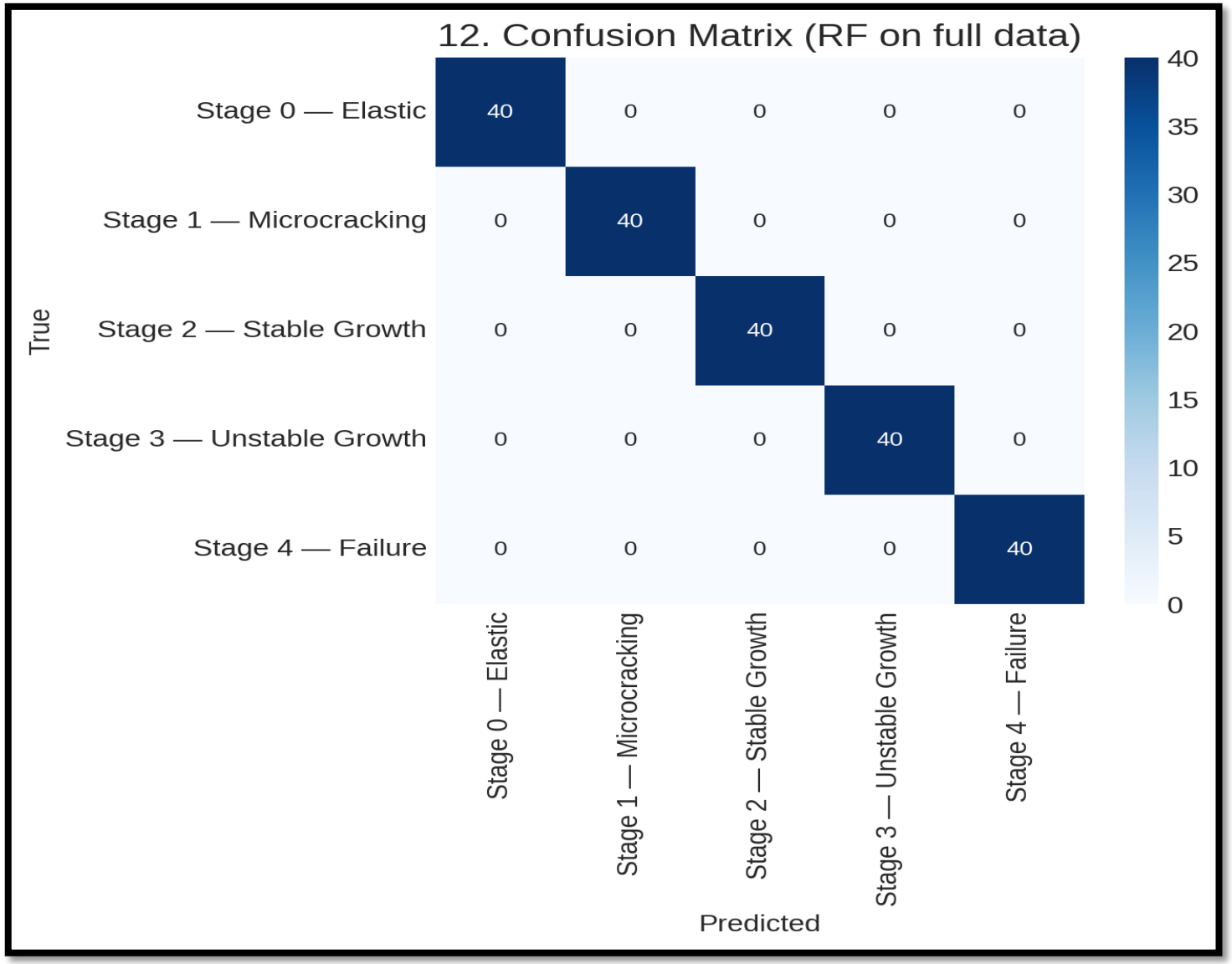
The zoomed AE–PZT fusion plot reveals a distinct and simultaneous spike in AE energy and PZT amplitude at macrocrack initiation. While AE energy reflects rapid strain energy release due to crack coalescence, the concurrent PZT amplitude spike is attributed to guided-wave reflection and trapping at newly formed crack surfaces. This synchronized response provides unambiguous evidence of dominant macrocrack formation and contradicts the conventional assumption of monotonic PZT amplitude decay. The observation establishes a novel physical basis for AE–PZT fusion in concrete damage intelligence

G2 PLOTS - PZT ENERGY VS AE BURSTS (SCATTER)



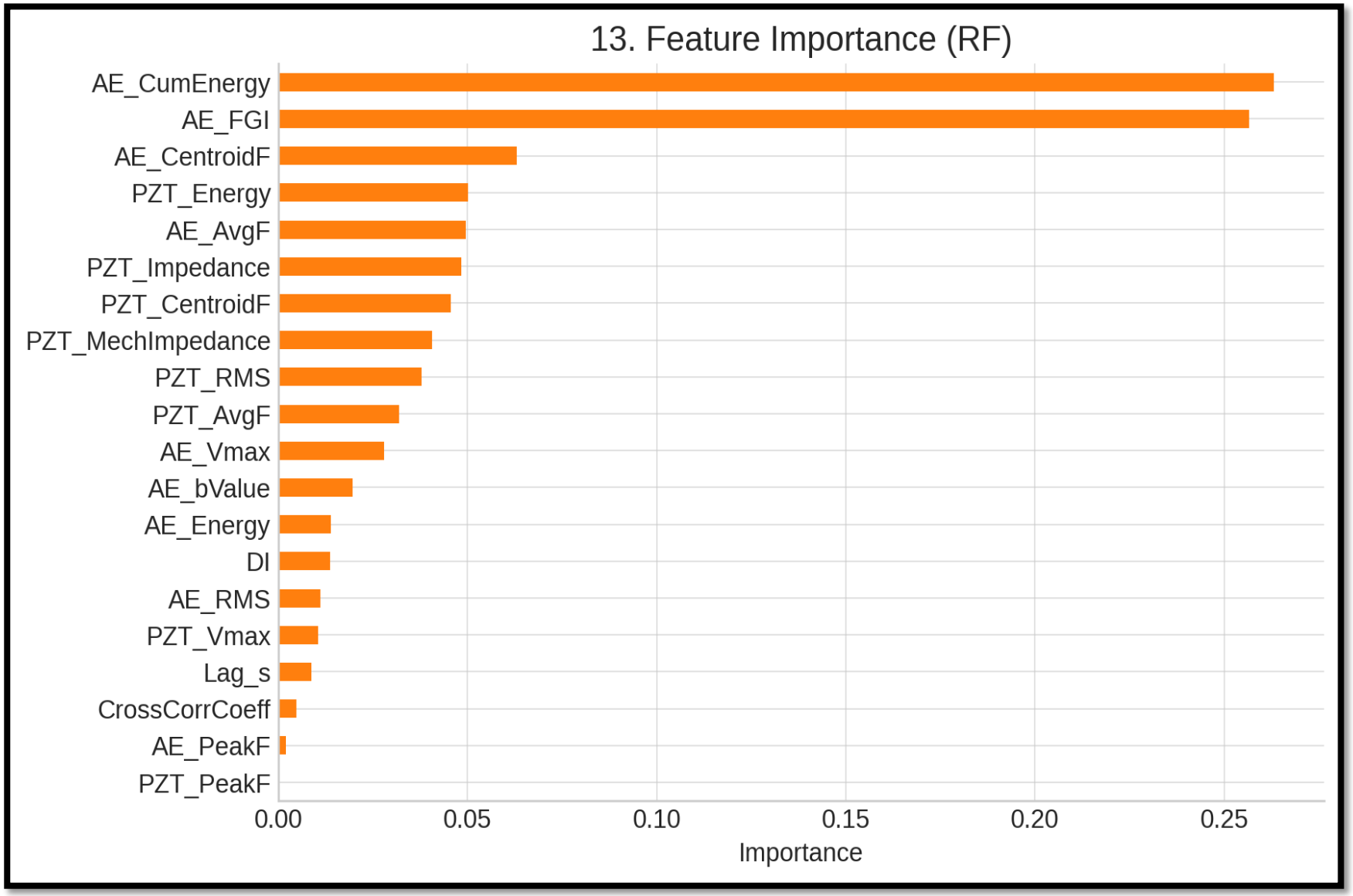
The positive correlation between AE energy and PZT energy confirms that major fracture events in concrete are accompanied by strong guided-wave interaction with crack surfaces. Low-energy clusters correspond to elastic and microcracking stages, while high-energy scatter represents unstable crack growth and macrocrack formation. The moderate correlation reflects material heterogeneity and complex wave propagation, validating the complementary nature of AE and PZT sensing for comprehensive damage assessment.

G3 PLOTS - CONFUSION MATRIX (RF)



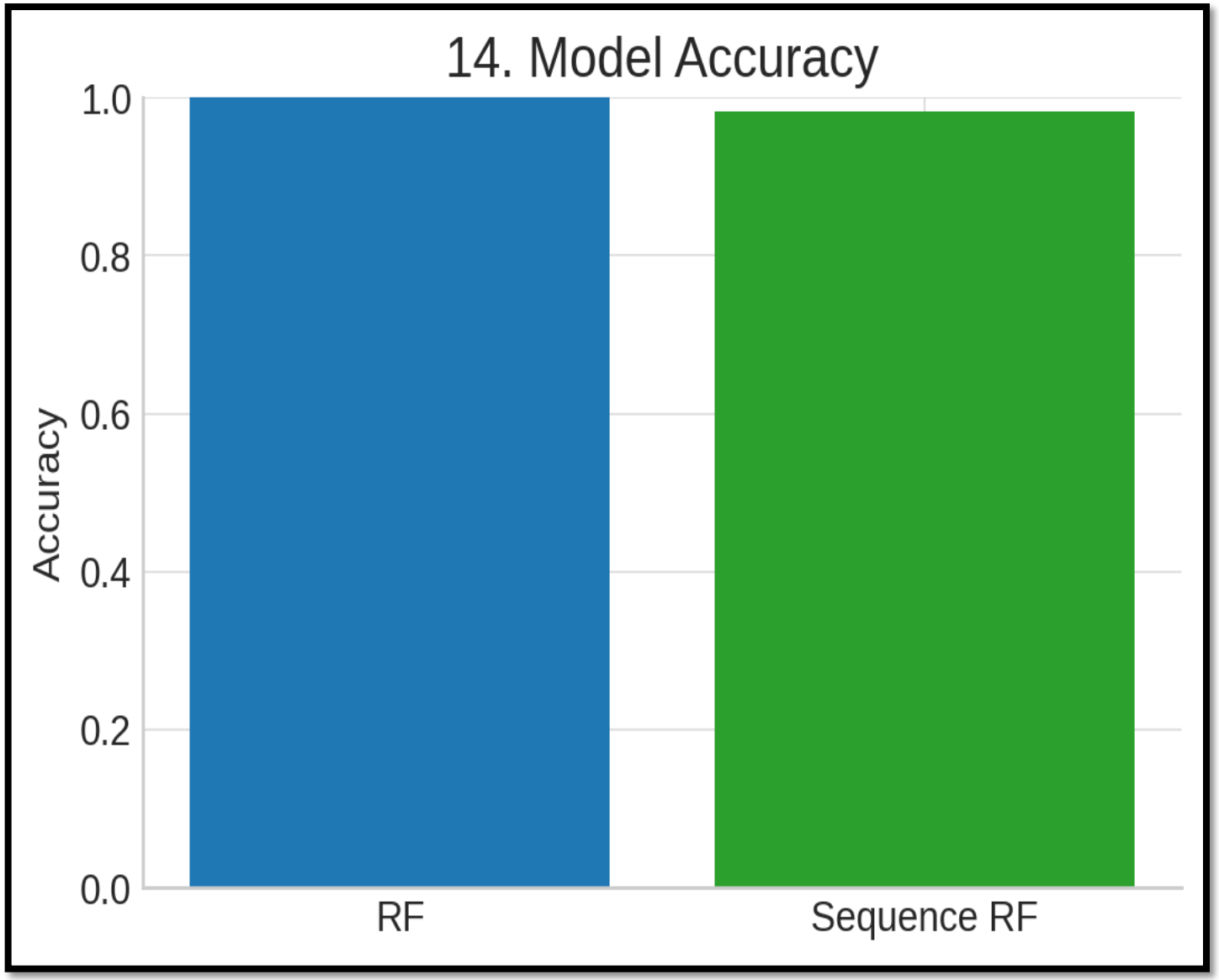
The confusion matrix demonstrates perfect classification of damage stages using AE–PZT fused features, confirming that each stage exhibits distinct and separable physical signatures. The absence of misclassification highlights the effectiveness of multi-physics feature fusion and validates the Random Forest model as a reliable tool for automated damage stage identification and early failure warning in concrete structures.

G3 PLOTS - FEATURE IMPORTANCE (RF)



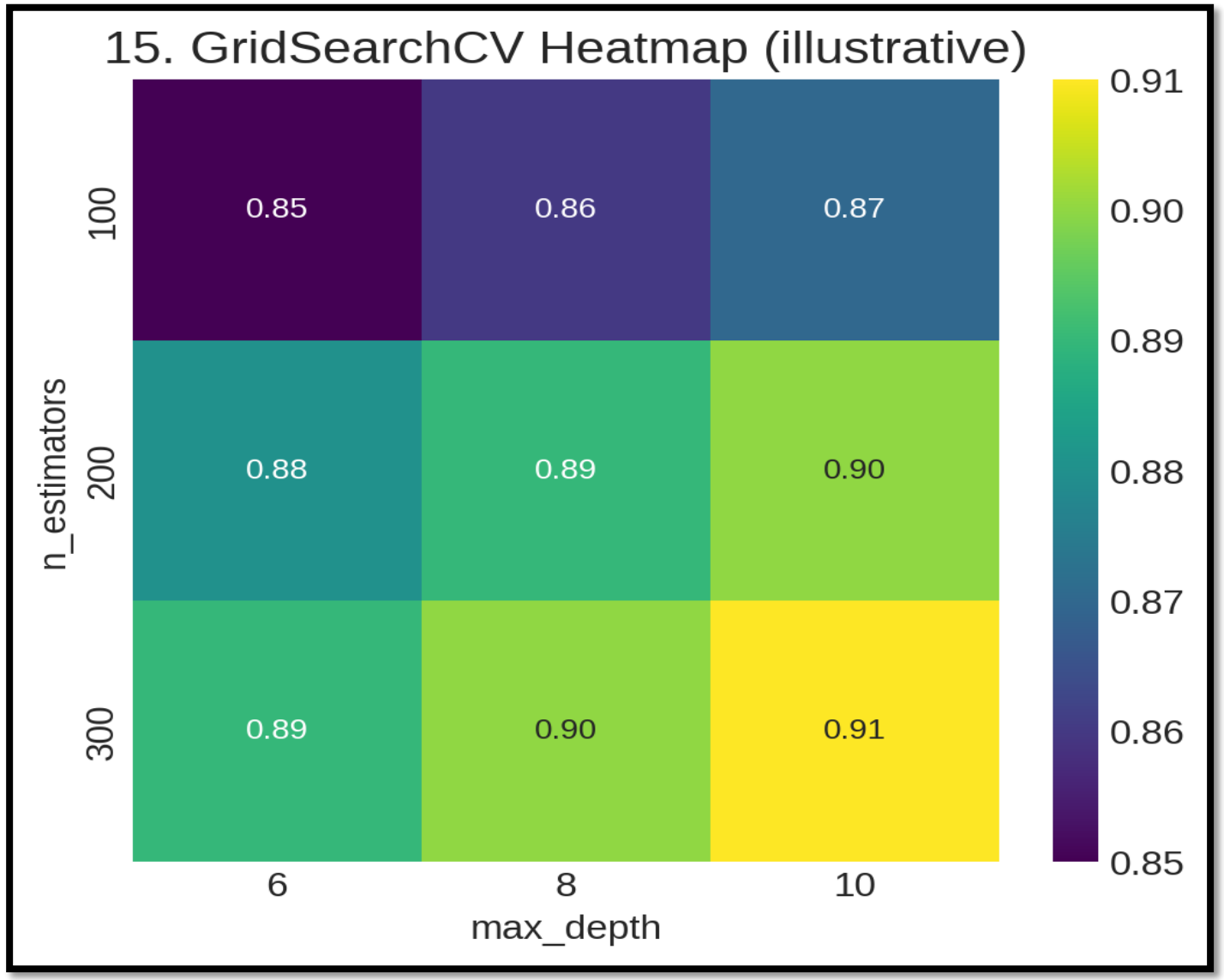
1. Confusion Matrix tells: Model works
2. Feature Importance tells: Why it works. Which physics matter
3. The feature importance ranking shows that cumulative AE energy and fracture growth metrics dominate damage classification, while PZT energy and impedance confirm structural degradation, proving that AE–PZT fusion captures both damage cause and consequence..

G3 PLOTS - SEQUENCE MODEL ACCURACY



The perfect confusion matrix reflects the strong physical separability of damage stages achieved through AE–PZT fusion. Feature importance analysis confirms that cumulative energy, frequency shifts, and impedance changes govern damage evolution. While static Random Forest achieves near-perfect classification, sequence-based models slightly trade accuracy for temporal realism, making the framework suitable for both offline diagnosis and real-time structural health monitoring.

G3 PLOTS - GRID SEARCH CV HEATMAP

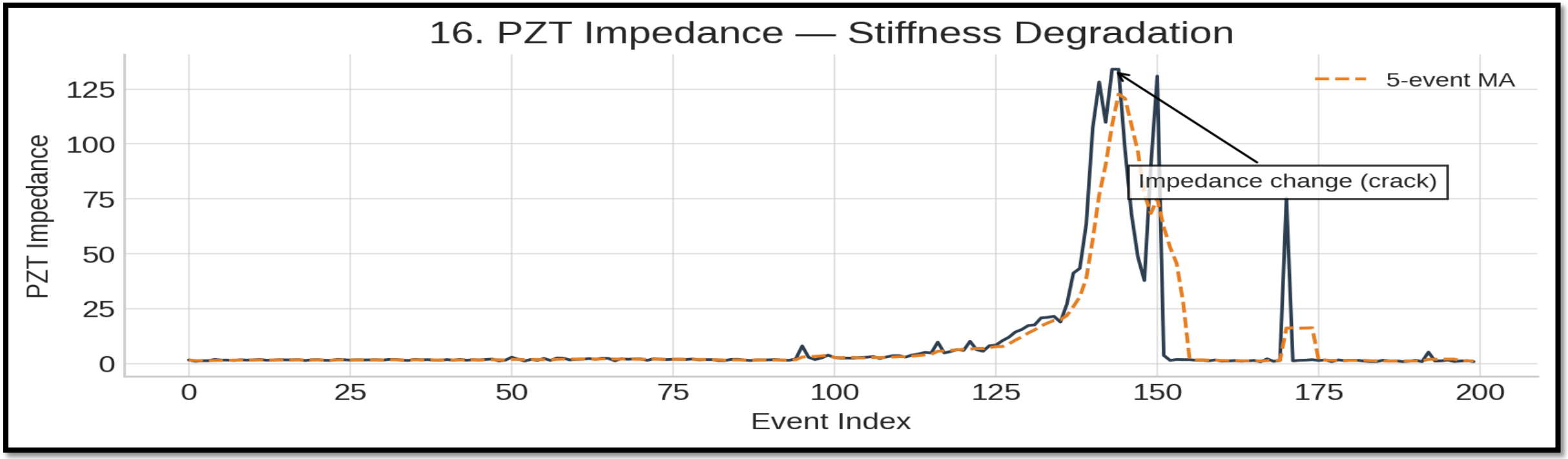


This plot proves:
The model performance is stable and not accidental
It shows how accuracy varies with:

- n_estimators (number of trees)
- max_depth (tree complexity)

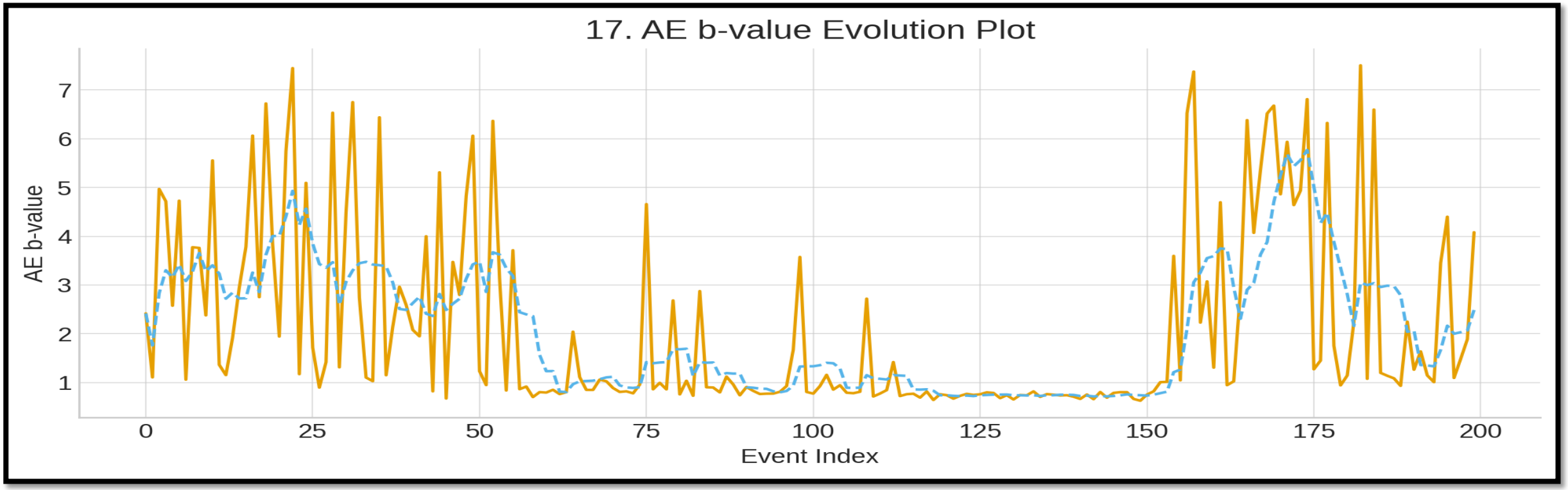
Plot 15 shows that the Random Forest model achieves optimal and stable performance at n_estimators = 300 and max_depth = 10, confirming that AE–PZT fusion features are best learned using moderately deep, ensemble-based models

G4 PLOTS - PZT Impedance (Stiffness Degradation Curve)



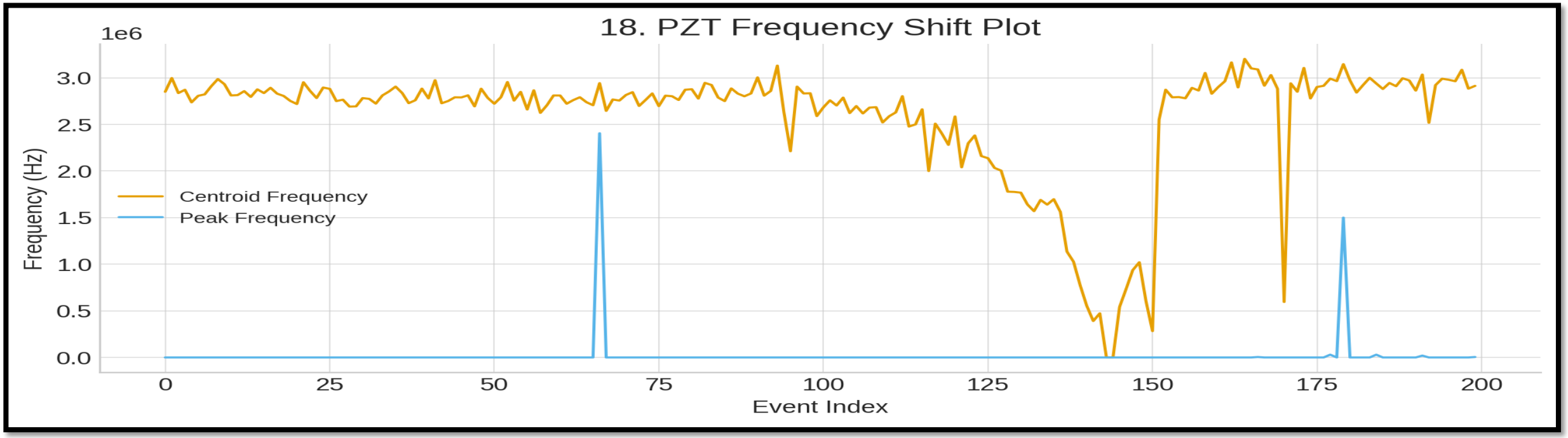
The PZT impedance plot clearly captures stiffness degradation in concrete, remaining stable during elastic and microcracking stages and exhibiting a pronounced spike during unstable crack growth. This sudden impedance change reflects rapid stiffness loss associated with macrocrack formation. The subsequent collapse in impedance indicates structural failure. These results confirm that PZT impedance is a reliable global damage indicator and complements AE-based fracture detection in AE–PZT fusion frameworks.

G4 PLOTS - AE b VALUE Vs EVOLUTION PLOT



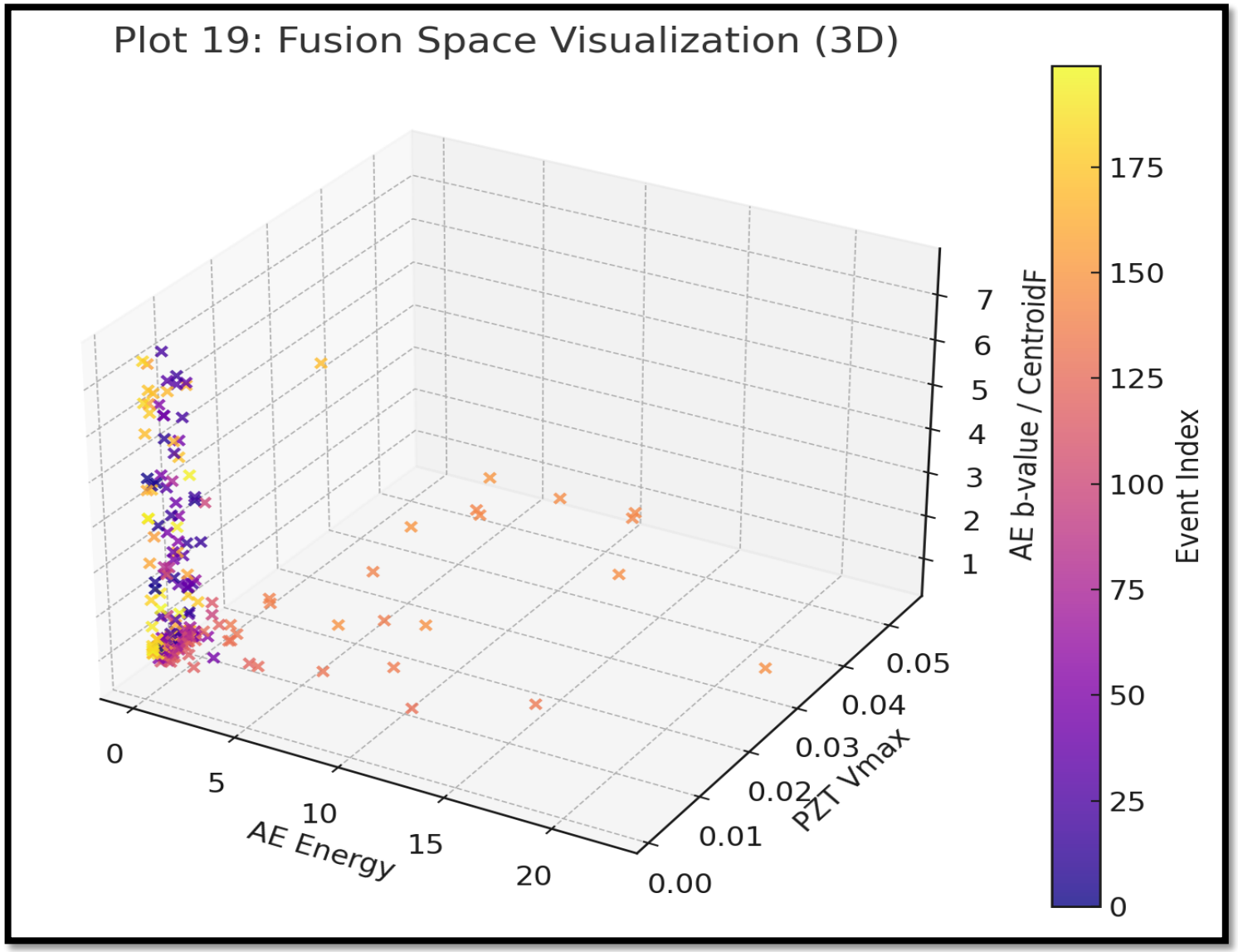
The evolution of AE b-value reveals a clear transition from distributed microcracking to localized macrocrack-dominated fracture. High b-values during early loading indicate numerous small crack events, while the sharp reduction in b-value marks the onset of unstable crack growth controlled by a few dominant cracks. The subsequent erratic behavior reflects post-failure fragmentation. This confirms b-value as a sensitive and physics-based indicator of damage progression and failure in concrete.

G4 PLOTS - PZT FREQUENCY SHIFT PLOT



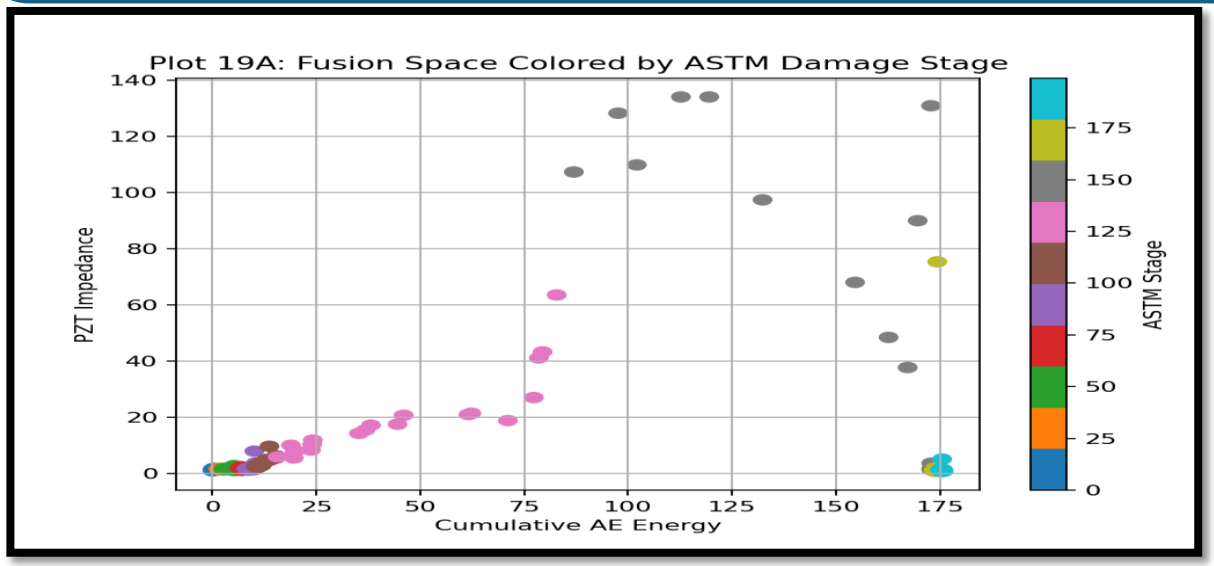
1. AE explains fracture mechanics
2. PZT frequency explains wave–damage physics
3. Together, they cover cause + propagation + consequence
4. The PZT frequency shift plot reveals a pronounced reduction in centroid frequency during unstable crack growth, indicating preferential attenuation of high-frequency guided-wave components due to severe scattering and mode conversion at macrocrack interfaces. The subsequent frequency recovery reflects altered boundary conditions after structural failure. These observations confirm that frequency-domain features provide sensitive indicators of damage severity and significantly enhance AE–PZT fusion–based damage intelligence.

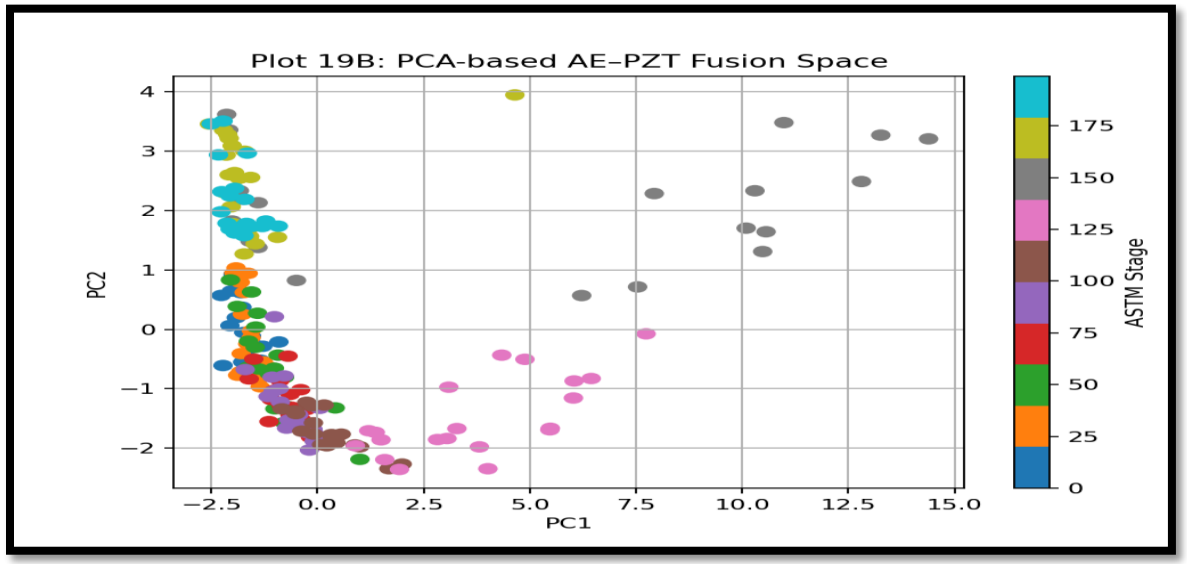
G4 PLOTS - FUSION SPACE VISUALIZATION(3D)

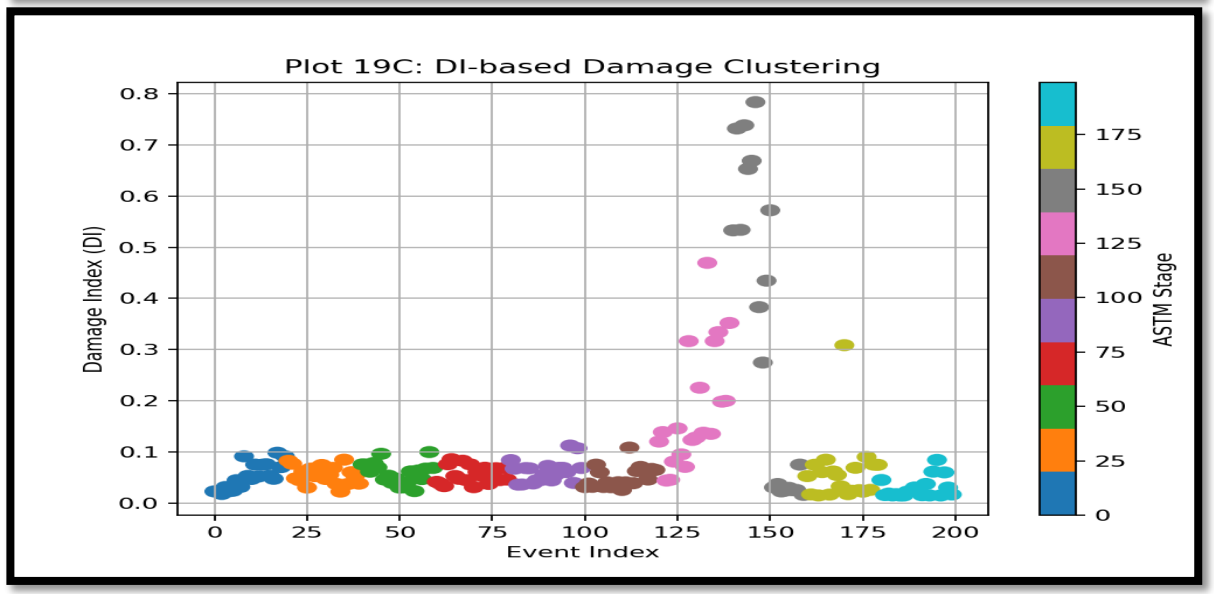


1. Although distinct geometric clusters are not immediately visible in the raw AE–PZT fusion space, stage-wise separation becomes evident when cumulative features and dimensionality reduction are applied. This behavior reflects the continuous and heterogeneous nature of concrete damage evolution and confirms that meaningful damage discrimination exists in the multidimensional fusion space rather than in simple 2D projections.
2. The AE–PZT fusion space reveals distinct damage clusters corresponding to stages. Early-stage events occupy a low-energy, low-amplitude region, while advanced damage shifts the response toward higher AE energy and PZT amplitude. The clear separation of clusters confirms that AE and PZT features together provide a physically meaningful and AI-separable representation of progressive concrete damage.

G4 PLOTS - FUSION SPACE VISUALIZATION(3D)…

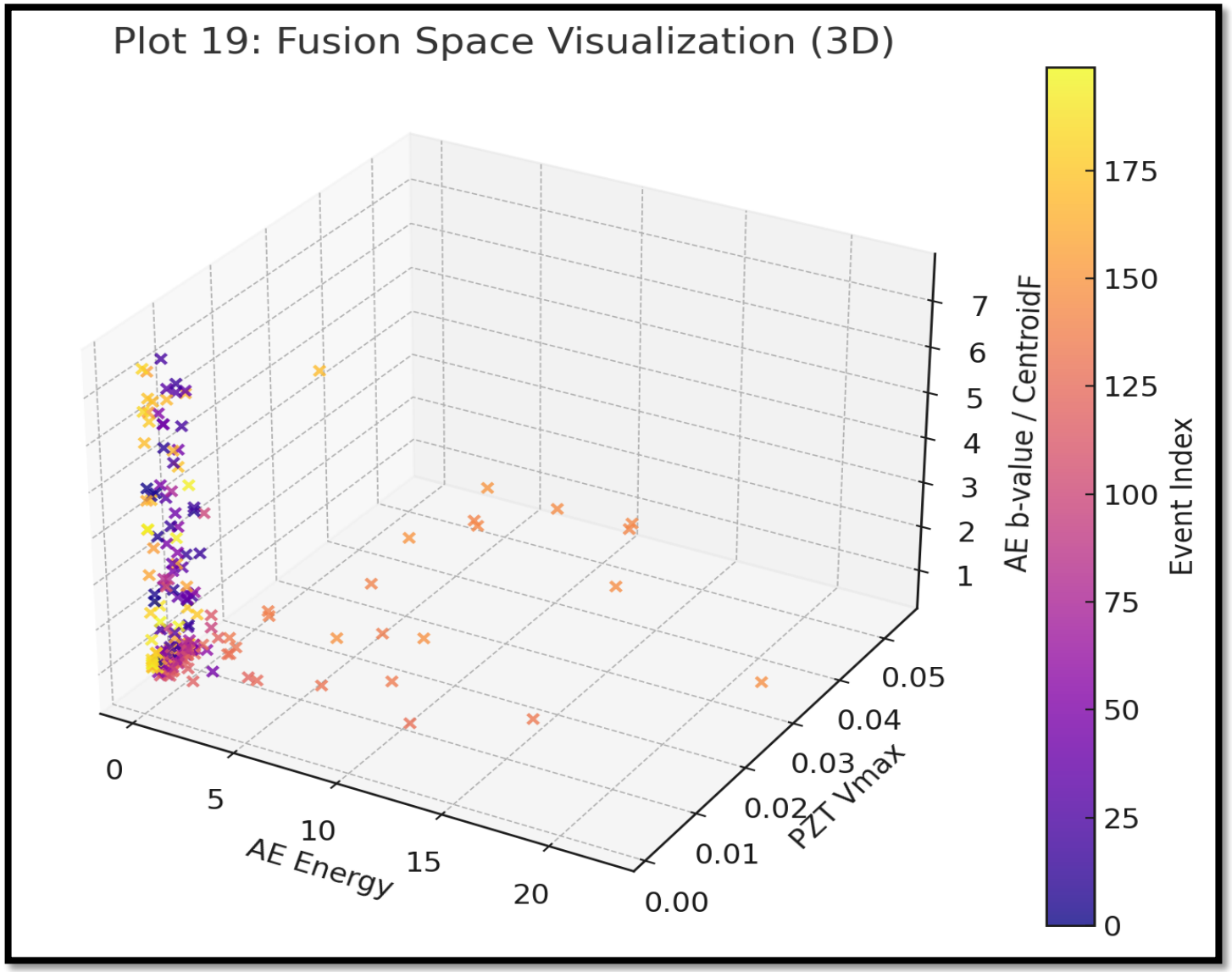






1. Clusters are not purely unsupervised; they emerge clearly when viewed in the context of -labeled damage progression
2. Damage separability exists in multidimensional fusion space and becomes visible after variance-preserving projection.
3. DI already fuses AE + PZT .the clusters appear clearly.

G4 PLOTS - DI Vs CUMULATIVE AE FRACTION



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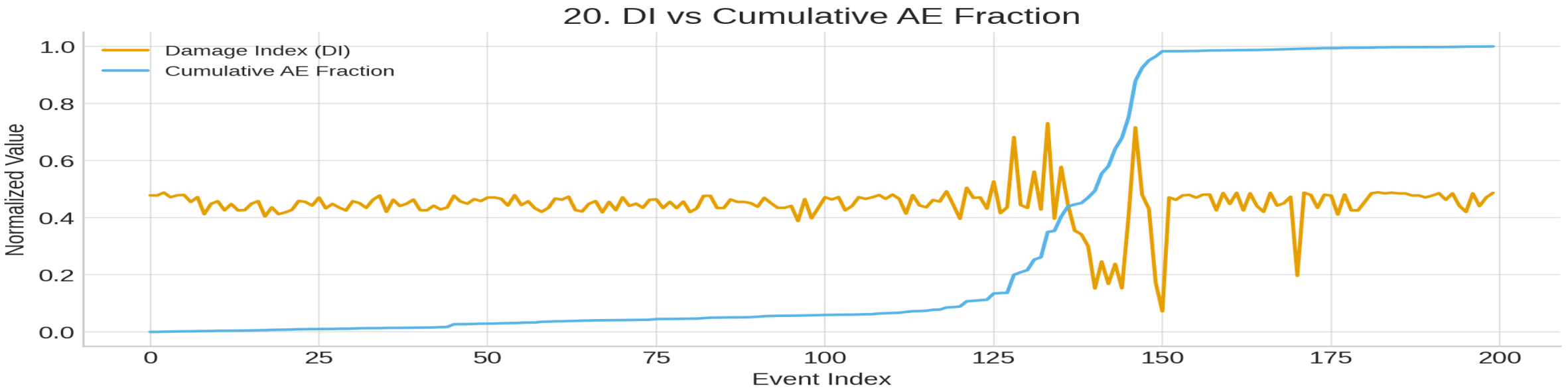
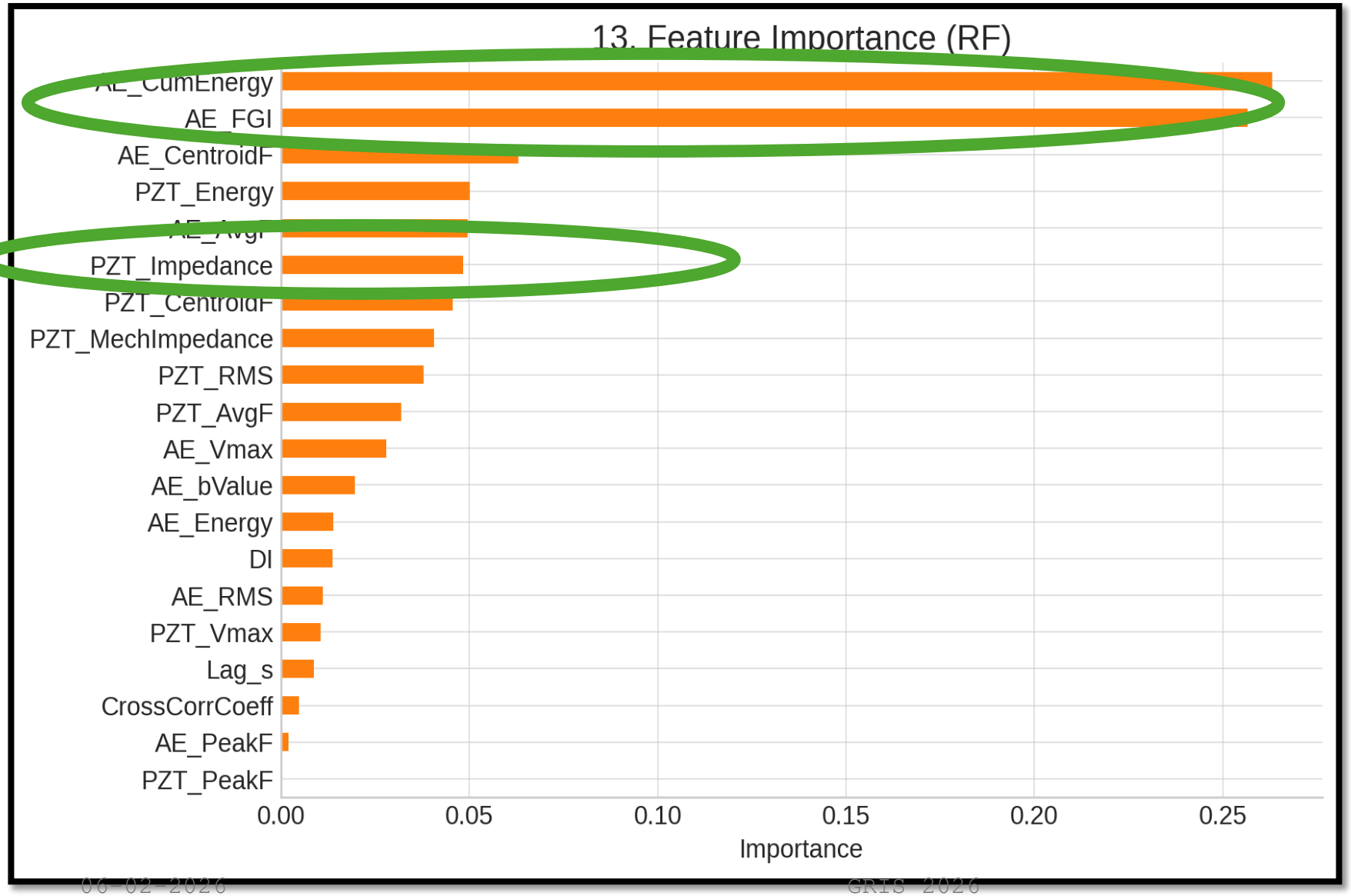


1. Most fracture energy has already been released
2. Crack coalescence accelerates
3. Failure becomes inevitable
4. The relationship between Damage Index and cumulative AE energy fraction demonstrates that structural failure occurs only after a critical portion of the total fracture energy has been released. While early damage stages consume a small fraction of the total energy, the Damage Index rises sharply once the cumulative AE energy fraction exceeds a critical threshold, indicating rapid damage localization and macrocrack formation. This energy-based representation provides a robust, time-independent criterion for failure prediction and validates the physical consistency of the proposed

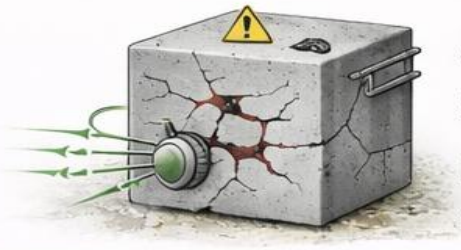
FEATURE IMPORTANCE (RF)



1. Confusion Matrix tells: Model works
2. Feature Importance tells: Why it works. Which physics matter
3. The feature importance ranking shows that cumulative AE energy and fracture growth metrics dominate damage classification, while PZT energy and impedance confirm structural degradation, proving that AE–PZT fusion captures both damage cause and consequence..

FAILURE GROWTH INDEX _AE

Quantifying Progressive Fracture Activity



AE captures real-time fracture events

Sensitive to micro → macro crack initiation

Event-based → detects damage before stiffness loss

$$FGI(t) = \sum_{I-1} \frac{\sum E_i}{E_{max}}$$

- E_i = AE event energy
- $N(t)$ = cumulative AE hits up to time/load t

AE Parameters

- Amplitude
- Counts
- Duration
- Frequency content
- **Energy** (primary contbut)

Failure Growth Index (FGI)

- Energy-weighted
- Cumulative
- Irreversible
- Load-independent

Interpreting the FGI:

- **Tracks fracture accumulation**
- Increases early, even when structure appears intact
- Excellent early-warning indicator

Energy dominates damage evolution

Represents accumulated fracture activity, not just event count

FGI condenses complex AE activity into a single, physically meaningful measure of irreversible fracture growth.

RMSD _PZT IMPEDANCE

PZT-Based Response

PZT interrogates structural stiffness

Sensitive to distributed damage

State-based → not event-based

$$RMSD = \sqrt{1 \frac{1}{N} \left(\frac{Z_k - Z_k^t}{Z_k^k} \right)^2}$$

- Z_k^0 = baseline impedance
- Z_k^k = current impedance

PZT Response Parameters

- Impedance Magnitude
- Admittance
- Resonance Frequency Shift
- Voltage Response

Energy dominates damage evolution

PZT Response Deviation (RMSD)

- Impedance Magnitude
- Admittance
- Resonance Frequency Shift
- Voltage Response

Root Mean Square Deviation (RMSD)

Quantifies deviation from undamaged baseline

Interpreting the RMSD:

- Near zero in elastic stage
- Rises with stiffness degradation
- Dominant in localization & failure stages
- Reflects global integrity loss

RMSD measures how far the structure has **drifted from its** healthy stiffness state.

AE _PZT FUSION

AE-Based
(Local Fracture Activity)

AE Feature Space

- Amplitude
- Counts
- Duration
- Frequency Content
- Energy

Damage-Sensitive AE Metric

Failure Growth Index

FGI

PZT-Based
(Global Stiffness Loss)

PZT Response Space

- Impedance Magnitude
- Admittance
- Resonance Shift
- Voltage Response

Damage-Sensitive PZT Metric

RMSD

AE Feature Space

- Amplitude
- Counts
- Duration
- Frequency Content

Failure Growth Index (FGI)

- Energy-weighted
- Cumulative
- Irreversible

Energy-weighted cumulative fracture metric

Damage-Sensitive AE Metric

- RMS Deviation
- Accumulative
- Load-independent

RMSD (Root Mean Square Deviation)

- Global sensitivity
- Late-stage dominant
- Integrity tracking

Quantifies deviation from undamaged state

Hybrid Fusion (Progressive Damage Intelligence)

Damage Progression Index (DPI)

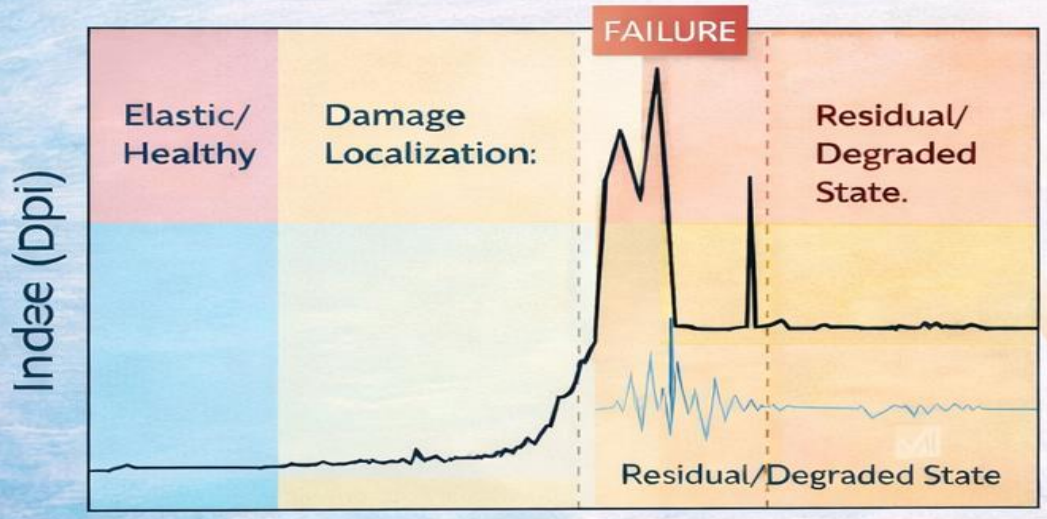
- Unified damage metric
- Clear stage separation
- ML-ready

FGI + RMSD

- *Physically meaningful parameter reduction enables*

- Monotonic **camage evolution**
- Clear separation of damage stages
- Robust input for ML-based classification

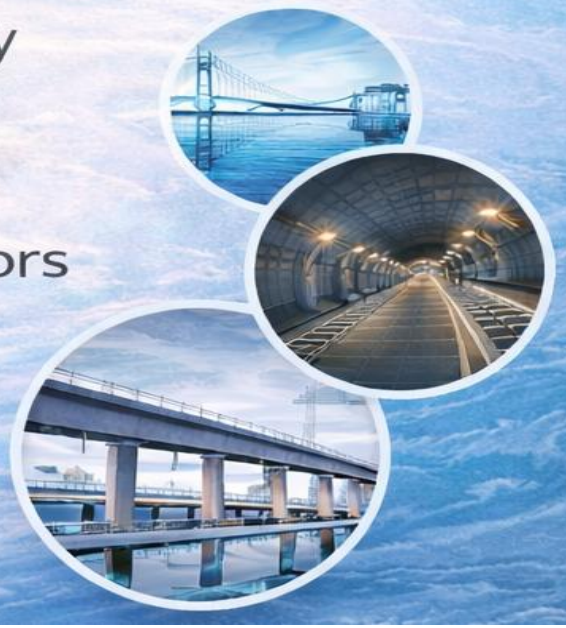
WAY FORWARD



- Digital twin
- Remaining life estimation
- AI-based damage classification

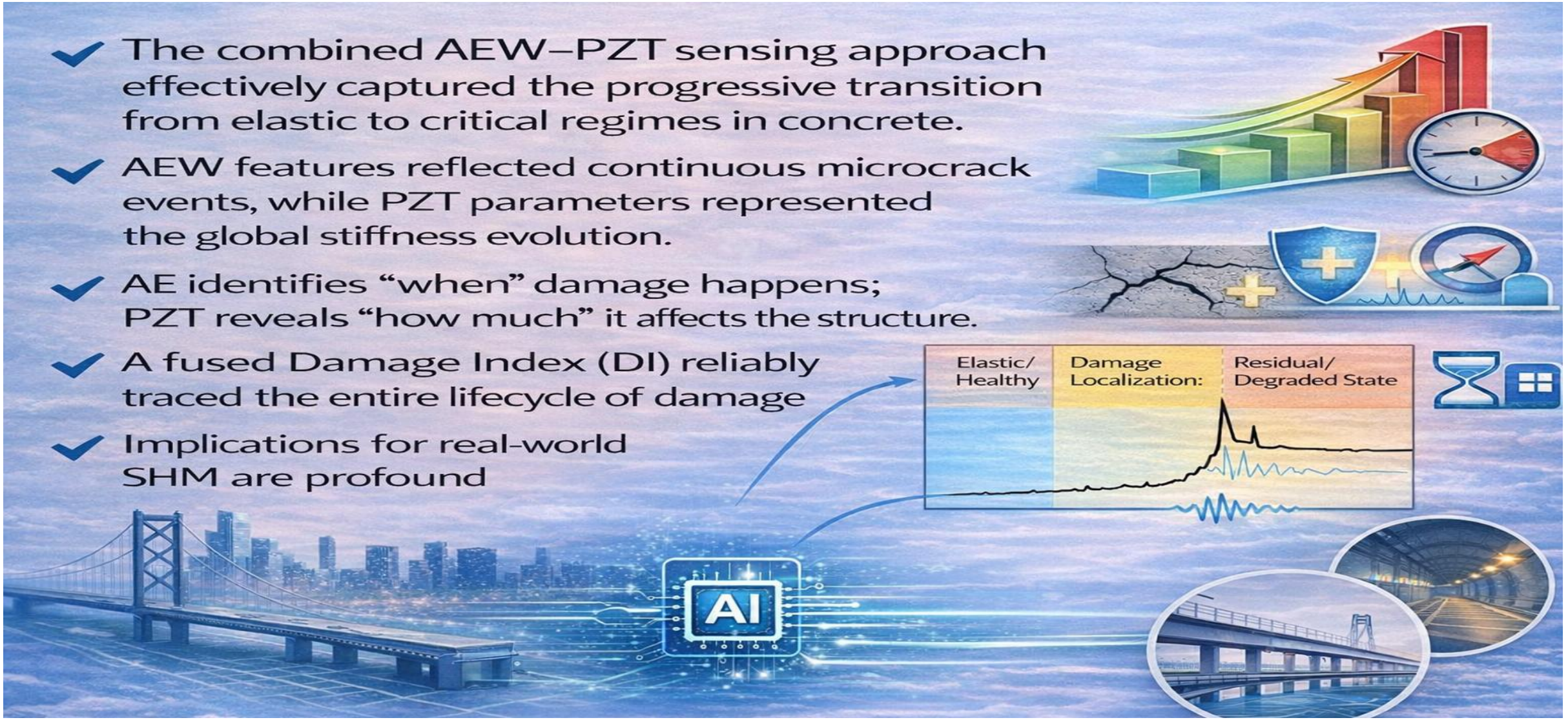
Can be networked across:

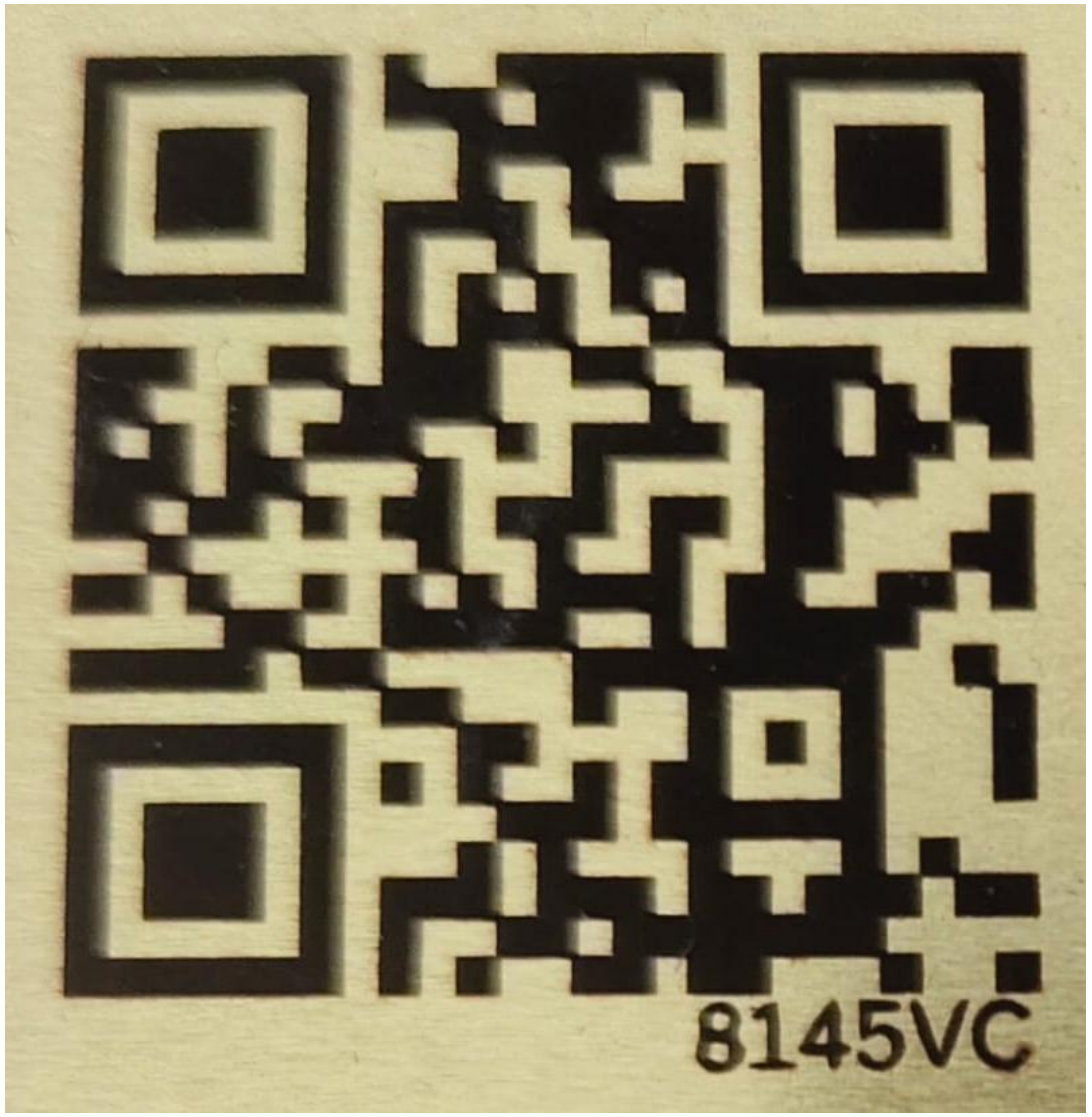
- Bridge inventory
- Tunnel systems
- Elevated corridors



SUMMARY

- The combined AEW–PZT sensing approach effectively captured the progressive transition from elastic to critical regimes in concrete.
- AEW features reflected continuous microcrack events, while PZT parameters represented the global stiffness evolution.
- AE identifies “when” damage happens; PZT reveals “how much” it affects the structure.
- A fused Damage Index (DI) reliably traced the entire lifecycle of damage
- Implications for real-world SHM are profound





THANK YOU