

Dual-Descriptor VAE Characterisation of AE-Band Structural Signals in Reinforced Concrete

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Summary:

We report an offline baseline-relative VAE study for fixed-window characterisation of continuous high-frequency structural acoustic signals from AE-band piezoelectric sensors in reinforced concrete. RMS-normalised spectra represent spectral shape, while pre-normalisation log-RMS preserves amplitude-related energy. In a bending test, principal load cycles were dominated by energy increases, with weaker spectral-shape shifts, latent-space drift, and broader latent dispersion during final load-to-failure. Results support unsupervised descriptor-based continuous signal characterisation under varying load.

Keywords: Continuous high-frequency structural signals, reinforced-concrete bending test, variational autoencoder, baseline-relative descriptors, AE-band sensing

Background, Motivation and Objective

We use AE-bandwidth piezoelectric sensors (30–120 kHz) but treat the recorded signals as continuous high-frequency structural acoustic time series, without hit detection or onset picking. AE-band sensing is widely used in concrete monitoring [1,2], where conventional hit-based workflows depend on threshold and onset choices - a well-known limitation across general AE signal processing [2,3]. Dense fixed-window processing avoids committing to a single hit definition and yields continuous time-series descriptors that can be aligned with the loading history. Normal-state Variational Autoencoder (VAE) [4] reconstruction has been used in related work to detect deviations from a reference state [5]. Building on this baseline-relative idea, this proof-of-concept study investigates an offline dual-descriptor VAE workflow during one reinforced-concrete bending test, with RMS-normalised spectrograms representing spectral shape and pre-normalisation log-RMS retained as the energy descriptor.

Description of the New Method

Two AE-band piezoelectric sensors mounted diagonally on a full-scale reinforced-concrete (RC) beam recorded continuous signals at 10 MHz, decimated to 1 MHz and segmented into 10 ms windows with 2 ms hop (80% overlap). The two synchronised channels were stacked as a joint two-channel spectrogram tensor. The joint pre-normalisation RMS was stored as the energy descriptor; waveforms were normalised by this RMS before STFT. STFT used a 1024-sample Hann window, 256-sample hop, 2048-point FFT, cropped to 30–120 kHz and standardised against baseline statistics. Load was

synchronously recorded by the testing-machine load cell; load values are used here to define load-cycle boundaries but are not used as input to the descriptor pipeline.

The VAE used a 128-dimensional latent space and was trained on 50,000 baseline spectrograms from 20–130 s. Training used Adam with an initial learning rate of 0.001 and cosine learning-rate decay, up to 100 epochs with early stopping, and a loss combining reconstruction MSE, a spectral-consistency term penalising frequency-band and time-envelope energy mismatch, and KL regularisation with β warmed up linearly to 0.003 over 15 epochs. The spectral-shape score is a one-sided RMS combination of the robust-standardised reconstruction MSE and spectral-consistency residual; negative deviations from the baseline median are clipped to zero. The energy score is the robust-standardised pre-normalisation log-RMS, using baseline median and robust scale. Encoder mean vectors are used to compute a robust-standardised latent-drift score relative to the baseline latent centre.

The loading programme comprised an initial zero-load reference period, a first load cycle peaking at ~24 kN (140–210 s), two intermediate ~10 kN holds (505–620 s and 900–940 s), a second load cycle peaking at ~51 kN (1100–1290 s), and a final load-to-failure cycle reaching ~70 kN (1380–1630 s). The present analysis focuses on baseline-relative drift across the three principal load cycles.

Results

The threshold-free descriptor view showed an energy-dominated response during the principal

load cycles, while the spectral-shape descriptor changed more gradually. This supports interpreting the two descriptors as parallel summaries of amplitude-driven and spectral-shape evolution in this single loading sequence, rather than as validated damage-class labels.

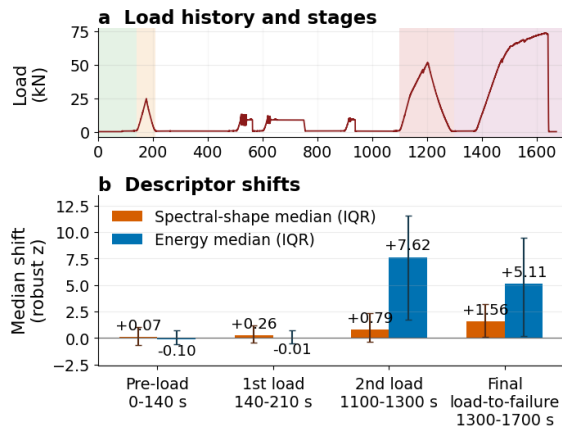


Fig. 1. Load history and baseline-relative descriptor shifts across the selected load stages. Bars show stage-wise medians and IQRs of robust-z-standardised descriptors without percentile-based event selection.

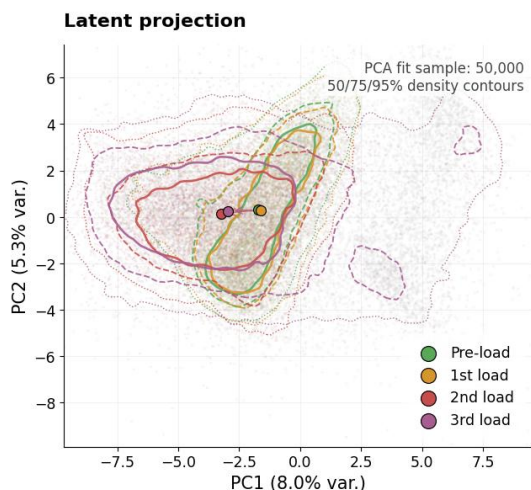


Fig. 2. Latent projection by load stage. PCA contours and centroids summarise stage-wise drift and dispersion in the VAE latent space.

The latent projection showed continuous stage-to-stage drift rather than isolated clusters. The later loading stages broadened in the displayed PCA space, consistent with a more variable latent representation during the high-load and failure sequence.

The framework provides parallel baseline-relative descriptors for offline characterisation of high-frequency structural acoustic signals under varying load in this case study. Operating-point calibration for engineering deployment is left to follow-up work, where multi-specimen baselines will enable systematic sensitivity analysis.

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