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Structural Health Monitoring and Earthquake/Climate Proofing by means of AI Sensor Fusion, Digital Twins and Smart Oracles

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INTRODUCTION & AIM

This work integrates AI-driven sensor fusion, Digital Twins, and Smart Oracles to overcome long-standing limitations in SHM, particularly fragmented data and unreliable climate information, developed by the Horizon Europe project BUILDCHAIN (https://buildchain-project.eu/). By unifying high-frequency structural data with verifiable environmental intelligence, the framework enables real-time, multi-hazard assessment and supports more confident decision-making across the building lifecycle.

METHOD

High-frequency acceleration and environmental measurements are processed through COV-SSI, OMA, and automated FE-model reconciliation, ensuring continuously updated structural parameters. These data streams feed a dynamic Digital Twin that recalibrates every two hours, enabling scenario simulations, predictive maintenance, and rapid anomaly detection (Fig. 1). Climate / environmental datasets retrieved via BUILDCHAIN oracles are transformed into validated Knowledge Assets and published on the DKG, ensuring traceability (Fig. 2). Climate hazards are assessed using extreme indices and EN1990-compliant analyses, while seismic vulnerability is evaluated through the E-PUSH nonlinear pushover algorithm. A NoSQL architecture supports ~1 GB/day ingestion and harmonizes heterogeneous pilot datasets. The proposed solution can benefit a broad range of stakeholders across the built-environment ecosystem. The proposed solution can benefit a broad range of stakeholders across the built-environment ecosystem (Fig. 3).

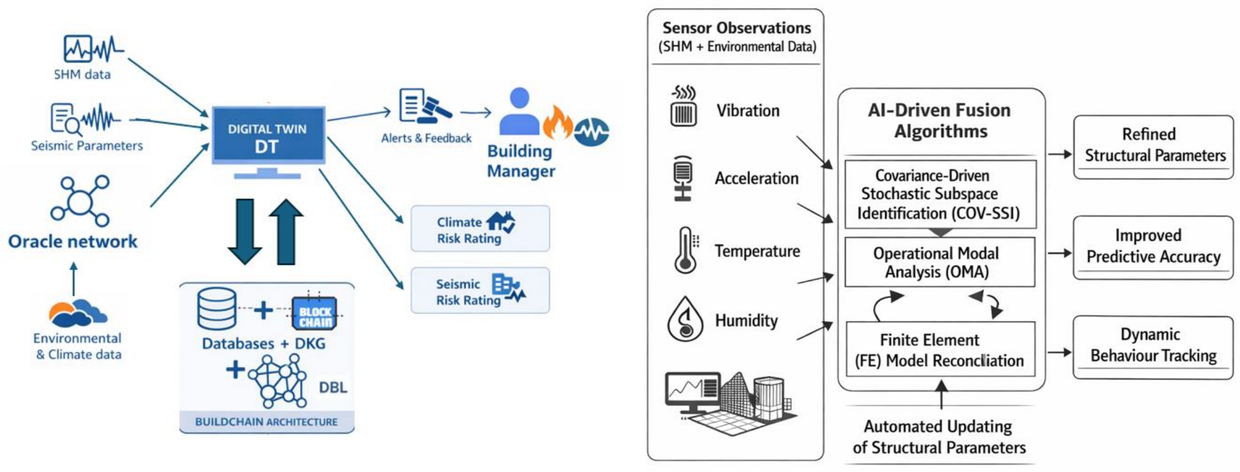

Fig. 1. Left: Proposed Architecture. Right: AI Driven Sensor Fusion and Model Updating

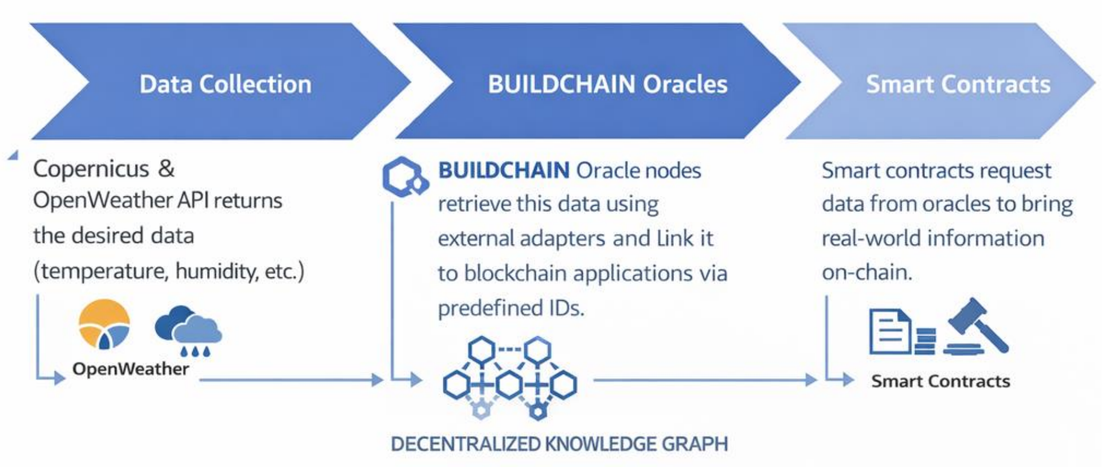

Fig. 2. Process Overview Related to BUILDCHAIN Oracles and Environmental / Climate data

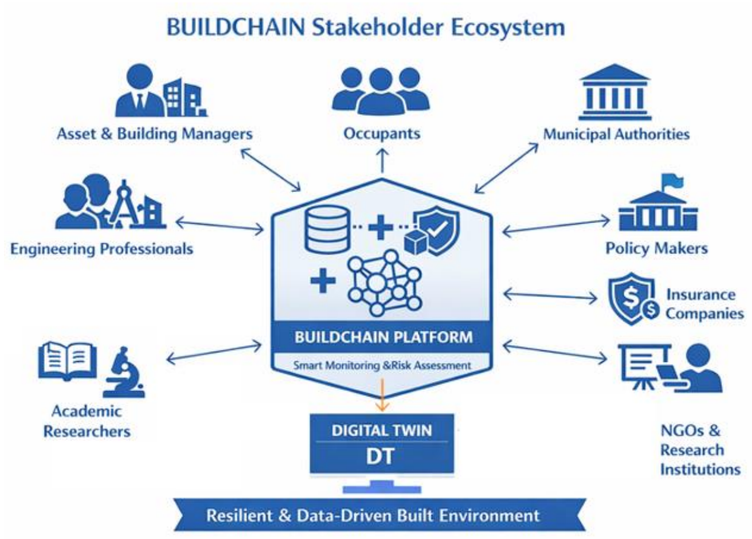

Fig. 3. BUILDCHAIN Stakeholder Ecosystem

RESULTS & DISCUSSION

AI-enhanced fusion and Digital Twin updating improved predictive accuracy in tall CLT buildings, refining elastic modulus scaling and narrowing the gap between as-designed and as-built performance. Deployments at the Hospital Real of Granada and Palazzo Poniatowski Guadagni demonstrated system robustness, enabling quasi-real-time modal analysis, dynamic DT generation, and automated anomaly detection. Oracle-enabled climate intelligence strengthened the ability to distinguish environmental effects from genuine structural changes, with hourly temperature and wind parameters emerging as key drivers. The system also supports proactive climate-hazard identification by comparing extreme forecasts with historical trends and issuing alerts to the DKG. Table 1 summarizes the results of the proposed BUILDCHAIN solution by presenting key performance categories alongside their anticipated directional trends

Table 1. Summary of Results

Category	Result	Trend
Predictive Accuracy	Improved vibration and structural performance prediction	↑ ~10%
Data Integrity & Reliability	Enhanced trust and traceability through blockchain governance and Oracles	↑ 100%
Model Updating	Faster and more reliable Digital Twin calibration	↑ ~20%
Operational Discrepancies	Reduced gap between as-designed and as-built performance	↓ ~20%
Maintenance Efficiency	Earlier detection of anomalies and proactive interventions	↑ ~50%
Risk Assessment	Automated, faster climate and seismic risk ratings	↑ ~30%
Decision Support	Improved insight for asset managers and policy makers	↑ ~100%
Manual Data Handling	Decreased need for manual input and validation	↓ ~70%

CONCLUSION

The combined use of AI-driven fusion, Digital Twins, and Smart Oracles significantly enhances SHM reliability and predictive capability. The BUILDCHAIN framework provides a scalable and interoperable foundation for multi-hazard assessment, enabling proactive maintenance, improved resilience, and more sustainable management of both modern and heritage buildings. By unifying verifiable climate data with automated model updating and continuously evolving Digital Twins, the approach advances toward smarter, safer, and climate-adapted built environments.

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