Title	Cracking location prediction and tensile strength estimation of UHPFRC based on deep learning
Author(s)	LUO, Xin
Degree Grantor	北海道大学
Degree Name	博士(工学)
Dissertation Number	甲第16621号
Issue Date	2025-09-25
DOI	https://doi.org/10.14943/doctoral.k16621
Doc URL	https://hdl.handle.net/2115/98231
Type	doctoral thesis
File Information	Xin_Luo_abstract.pdf, 論文内容の要旨 https://creativecommons.org/licenses/by/4.0/

学　位　論　文　内　容　の　要　旨

博士の専攻分野の名称　　博士（工学）　　氏名　LUO Xin

学　位　論　文　題　名

Cracking location prediction and tensile strength estimation of UHPFRC based on deep learning
(深層学習に基づく UHPFRC のひび割れ位置予測および引張強度推定)

Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) represents a state-of-the-art class of cementitious materials characterized by its superior mechanical properties, including exceptionally high tensile and compressive strength, excellent energy absorption, and remarkable durability. These attributes stem primarily from its highly compact matrix and the inclusion of randomly dispersed high-strength steel fibers, which significantly enhance crack resistance and post-cracking ductility. Despite these advantages, a major barrier to the widespread adoption of UHPFRC lies in its intrinsic heterogeneity, particularly the non-uniform distribution and orientation of steel fibers introduced during the casting process. Localized fiber deficiencies or clustering can create weak zones susceptible to early crack initiation, thereby undermining the reliability and performance of structural elements under load. This variability presents a significant challenge in predicting mechanical behavior and ensuring quality assurance in practical engineering applications.

To overcome these limitations, this dissertation proposes a comprehensive, non-destructive framework for predicting cracking locations and estimating tensile strength in UHPFRC based on high-resolution X-ray Computed Tomography (CT) imaging and advanced deep learning techniques. The proposed methodology bridges the gap between internal fiber architecture and macroscopic mechanical performance by combining data-driven detection of fiber-deficient regions with micromechanical modelling informed by spatially resolved image features. The research is structured around two main objectives: (1) to develop a deep learning-based approach for identifying potential cracking locations under both flexural and tensile loading conditions, and (2) to estimate tensile strength by analysing local fiber orientation and efficiency at the predicted crack locations.

In the bending domain, four-point flexural tests were performed on UHPFRC beam specimens to investigate the correlation between internal fiber characteristics and cracking behavior. CT imaging enabled the reconstruction of internal fiber distributions, which served as the foundational dataset for model development. A YOLOv8 object detection model was initially adopted to predict cracking locations by identifying fiber-deficient regions. Although promising, the model’s ability to detect fine structural features was limited by spatial resolution constraints and insufficient contextual understanding. To address these issues, an enhanced version, YOLOv8-DC, was proposed, integrating deformable convolutional networks and coordinate attention modules. This modification improved detection accuracy and robustness, elevating the prediction success rate from 76.2% to 79.1% while reducing model size and computation cost. Ablation studies further confirmed the individual contributions of each module, demonstrating enhanced localization and feature discrimination capacity.

In the tension domain, a series of uniaxial tensile tests were conducted on dog-bone-shaped specimens cast using four different methods to generate diverse fiber distributions. Mechanical tests demonstrated a clear link between casting method, fiber count within the gauge length, and tensile behavior. Based on CT-derived fiber characteristics, a YOLOv11 model was developed for cracking location prediction under tensile loading, yielding a success rate of 73% in strain-hardening specimens but only 17% in strain-softening ones, due to the unpredictable external crack formation in the latter. To further improve spatial robustness, a cracking path prediction approach was introduced, segmenting each specimen into three longitudinal regions and quantifying detection frequencies. Comparison with Digital Image Correlation (DIC) strain maps revealed that 67% of specimens achieved an average Intersection over Union (IoU) exceeding 50%, affirming the method’s ability to capture distributed cracking evolu-

tion. This path prediction approach was particularly effective in strain-hardening specimens exhibiting multiple microcracks.
Following the cracking location prediction, tensile strength was estimated at predicted cracking locations using a micromechanical model incorporating CT-derived orientation and efficiency factors. An interfacial bond strength of 12.5 MPa was back calculated from experimental data, and the estimated tensile strength was compared against both experimental and theoretical values at actual cracking locations. For strain-hardening specimens, the average error between the estimated tensile strength at the predicted cracking location and the experimental tensile strength was 5.72%, and between the estimated tensile strength at the predicted cracking location and the theoretical tensile strength at the actual cracking location was 3.34%, indicating excellent agreement. In contrast, strain-softening specimens exhibited substantial errors, primarily due to failed cracking location prediction and ineffective fiber bridging at actual cracking locations. Detailed error analysis confirmed that successful cracking location prediction was essential for reliable tensile strength estimation, and that casting methods significantly influenced both fiber uniformity and model performance.
In this study, a robust and versatile framework was developed for non-destructive cracking location prediction and tensile strength estimation in UHPFRC, integrating high-resolution CT imaging with enhanced deep learning models. It was demonstrated that the prediction of cracking behavior, particularly under flexural and tensile loading conditions, could be significantly improved by incorporating deformable convolution and coordinate attention mechanisms into the detection network. Compared to conventional guidelines such as SIA 2052-2016, the proposed framework enables pre-failure evaluation of mechanical performance without destructive sectioning, which is critical for ensuring structural safety in real applications. However, most existing studies on UHPFRC performance have not fully considered the role of internal fiber architecture in predicting both cracking location and tensile strength. This limitation may result in inaccurate estimation of load-carrying capacity and ineffective structural design, especially when applied to critical infrastructure. In contrast, the present methodology bridges this knowledge gap by coupling deep learning technology with micromechanical modelling, offering quantitative predictions with strong experimental agreement. In general, the insights into fiber-governed cracking and strength behavior, obtained through deep learning and CT analysis, could not have been revealed through conventional observation or limited testing alone. This not only highlights the effectiveness of the proposed predictive approach but also provides a reference for future data-driven applications in UHPFRC-based smart design and real-time health monitoring.