論文の要旨

題目：ESTABLISHMENT OF DURABILITY DESIGN TECHNIQUES TO PREVENT SPALLING OF FACADE CLADDING IN RC BUILDINGS

(RC 建築物の外装仕上げ材の剥離防止に関する耐久設計技術の確立)

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The most prominent non-structural element in buildings, facade cladding, expresses design aesthetics while protecting structural components from weather. The most common cladding for RC buildings in Japan is rendered and tiling; however, it faces severe durability issues due to poor design, material selection, and inadequate maintenance, causing a high degree of deterioration. Typically, these claddings are composed of numerous layers of cementitious materials, with delamination being the predominant anomaly, especially between the rendering mortar and the concrete substrate. Cladding delamination can cause public safety incidents and shorten the building's lifespan. Furthermore, the lack of reliable methodologies and indications for assessing the durability of facade cladding makes it challenging to raise the standard of such material.

In this sense, this study aims to develop durability design techniques that can be implemented to reduce and prevent the facade cladding from peeling and spalling over time. Pre-construction performance design and in-operation preventative maintenance are crucial facade's life cycle stages. For the former, a laboratory-scale durability assessment method to rapidly screen materials and application procedures is established; for the latter, a cladding delamination detection technique that balances accuracy and timeliness is proposed to increase execution efficiency.

For the performance design phase, a lab-scale durability assessment method was proposed for rendering mortar/concrete adhesion that enables stakeholders to choose specifications based on predetermined targets. This technique applied a cyclic thermal load to a part of the rendering mortar surface to accelerate the degradation; this part represents an external wall subjected to solar radiation. Numerical simulation and experimental results support the effectiveness of the proposed accelerated degradation method. This technique deviates from the norm because it does not employ a combination of hot-cold and dry-wet cycles and only applies "partial" loads. Both are necessary for the accurate reproduction of the degradation mechanism; the former prevents erroneous reproduction of the collaborative action of the degradation agents and guarantees deterioration, while the latter offers sufficient constraints. Considering the rate of decrease in the bond strength as a criterion to evaluate the durability, the influence of several known factors on the durability can be explicitly ranked.

The proposed durability assessment method is appropriate for evaluating the long-term adhesion between multiple cementitious materials and is an efficient parameter screening instrument for product development. These tests reflect how the material should respond to solar radiation. Comparing it to a reference material with a lengthy application history allows a quick determination of whether the new material has the required durability. Furthermore, the investigation revealed that the deformation adaptability of the rendering mortar and concrete has a critical impact on their long-term adhesion. In this case, the compatibility of the material's dry shrinkage, elastic modulus, and coefficient of thermal expansion will be a linchpin of the durability design.

For the preventative maintenance phase, delamination detection techniques play a crucial role in maintaining the safety of the cladding. Unfortunately, several general approaches, such as percussion inspection and infrared thermography, fail to reconcile timeliness and accuracy. In this study, Fibre Bragg grating sensors, typically employed for structural health monitoring, were attempted for damage detection of claddings. Based on the relationship between the strain behavior of the materials, the technique identifies the delamination. The adhesive interface of any two cladding composition materials (concrete, rendering mortar, tiles, and tile adhesives) was examined. The experimental findings show that the FBG sensor's ability to track the composites' strain enables the detection of damage at any adhesive interface. In addition to qualitative damage identification, this approach can distinguish between three distinct adhesion states based on strain behavior, making it more precise than existing bonding performance tests.

-Healthy adhesion. A constant strain amplitude ratio is maintained, for example, and the strain behavior between the material's layers maintains some correlation.

-Adhesion damage (partial debonding) The two materials lose their ability to follow each other's deformation when their strain trajectories diverge, and their strain amplitudes abruptly decrease or increase.

-Adhesion failure (complete debonding). With a considerable shift in strain amplitude, the relationship between the strain behavior of the materials is entirely different from the first one.

In general, the determination of adhesion damage can be based on the loss of the initial following between the strain trajectories of the two materials. When the load is constant, an aberrant strain response, such as a quick increase or reduction, indicates a lesion. This technique's advantage is that continuous detection alerts building managers when intervention is required. If strain behavior demonstrates a lack of followability, one should be cautious and increase the frequency of inspections; if strain behavior becomes severely abnormal, one should consider repairing or replacing the affected components. This technique can prevent premature or delayed maintenance, accidental cladding peeling, and high maintenance expenses.

While establishing the above techniques, the debonding evolution of rendering mortar was investigated. On the scale of bond strength tests, debonding does not progress at a constant pace, and the mortar's adhesion weakens in an "S-shaped" pattern, stalling at a "plateau" period. During this time, the bond strength does not diminish with the aging cycle. Based on the material's strain behavior, it can be extrapolated that the "plateau" may represent the cumulative phase of mechanical bonds broken at the interface. During this period, progressively weaker adhesion between materials can be identified by strain behavior, while the bond strength test has hysteresis, requiring the debonding area to cumulatively approach a threshold before it can be characterized. This finding supports continuous damage detection’s significance in improving detection efficiency and accident prevention.

This dissertation summarizes a series of studies to develop durability design techniques. The goal of this research is to furnish professionals within the relevant field with practical tools that can effectively enhance the execution efficiency of all phases of a building's life cycle. The insights presented in this study hold potential for transforming the industry under consideration and extend the building's service life from their very inception.