Shallow crack effect in residual tensile strength evaluation of finite-sized structures made of ductile materials

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論 文 名　：Shallow crack effect in residual tensile strength evaluation of finite-sized structures made of ductile materials
（延性材料にて作成した有限サイズ構造の残存引張り強度評価法における浅いき裂効果）

区　　分　：　甲

論 文 内 容 の 要 旨

Residual strength, which reflects the practical load-carrying capacity of pre-damaged structures, is a critical concern in fail-safe design. As a representative case of local stress intensifiers, pre-existing cracks (pre-cracks) in engineering structures have attracted the most attention of residual strength investigations. Conventionally, residual strength issue of pre-cracked structures is solved by fracture mechanics with a presumption of the unstable crack propagation dominating the loss of load-carrying capacity. That is, fracture instability characterized by fracture instability toughness is regarded as the physical meaning of residual strength. With the joint efforts of mechanical and material researchers, however, the pre-cracks are becoming mechanically shallower, and the materials are becoming stronger and tougher, resulting in an extremely-high fracture instability toughness that makes the unstable crack propagation hardly occur. Hence, as plasticity develops with loading, if plastic instability, such as necking, instead of fracture instability dominating residual strength of shallow pre-cracked structures, most previous studies probably become invalid.

Moreover, the plastic instability dominating residual strength can challenge the general viewpoint of engineering that cracks weaken structures. First, as an extreme case of notch that the notch root radius approaches to zero, crack is widely considered to have no strengthening effect, such as notch strengthening, because unstable crack propagation is believed to occur at low stress. However, this situation will be changed if plastic instability can dominated the residual strength of shallow pre-cracked structures as a result of that plastic localization induced by crack can resist the general yielding and plastic instability. Second, extremely-high fracture toughness of shallow cracks may tune the influential factors that can enhanced the plastic strain localization near the crack-tip into positive factors for residual strength. These assumption is necessary to be verified due to the insufficient study of residual strength in the presence of shallow pre-cracks.

Regarding these concepts, this dissertation is focused on the residual tensile strength of shallow pre-cracked structure made of interstitial-free (IF) steel. The method of introducing shallow pre-crack on laboratory specimen, the clarification of trends, physical meanings and corresponding damage characteristics of residual strength, the prediction of residual strength in the case of plastic instability prevailing, and the influence of plastic strain localization altered by influential factors, especially the hydrogen, on residual strength are the emphasis of this study. The definition of shallow crack for residual strength issue, a novel failure-assessment diagram and a new classification of hydrogen-embrittlement susceptibilities were proposed for extent residual strength theory into shallow crack region.

This thesis consists of 6 chapters. All chapters are arranged to serve the central theme of ‘shallow crack effect on residual tensile strength evaluation’. The thesis outline is as follows:.

Chapter 1 described the general introduction of this study. The development and present level of residual strength study were briefly reviewed to propose a clear and unified definition of residual strength for this study. After indicating the potential physical meanings of residual strength, the research gap in residual strength of shallow pre-cracked structures was pointed out. Then, the motivation of this study, namely, improving the residual strength theory in the case of shallow cracks, was formed. The main objectives and originalities of each part of this study were described.

Chapter 2 solved the prerequisite for investigating the residual strength of shallow pre-cracked structures, that is, the identification of shallow crack-like notches for structural failure. Introducing crack-like notches is essential for this study because fatigue pre-cracking fails to ensure geometric symmetry, pre-crack measurability, and restricted pre-strain of shallow pre-cracked structures under plane strain condition. However, the results obtained by previous studies related to crack-like notches under small-scale yielding are invalid for shallow notches with extensive plasticity, particularly when plastic instability instead of fracture instability governs the residual strength. From the perspective of asymptotic and phenomenological analysis, this chapter proposed a novel criterion for shallow crack-like notch identification.

Chapter 3 clarified the trends, physical meaning, and corresponding damage characteristics of residual strength with shallow pre-crack depth. Results showed that the residual strength of shallow pre-cracked specimens was preferentially governed by plastic instability instead of fracture instability. Furthermore, when shallow pre-crack depths were shorter than a critical value, the rupture occurred in the intact cross-section and the residual strength was identical to the tensile strength of smooth specimens. Such an anti-commonsense phenomenon was explained from the perspective of plastic strain localization. Finally, the ‘shallow crack effect’ special for residual strength issues was defined.

Chapter 4 focused on predicting the residual strength of shallow pre-cracked structures. The prediction was divided into a qualitative part and a quantitative part. A novel failure assessment diagram correlating to physical meanings of residual strength and damage characteristics was suggested for qualitative predicting the trends of residual strength from the perspective of plastic strain localization. Meanwhile, a new classification of pre-cracks was proposed according to the physical meaning and corresponding damage characteristics of residual strength. The quantitative prediction was expected to be numerical and phenomenological because users can easily find out when the prediction method fails. It was implemented by finite element analysis based on continuum mechanics. Then, we evaluated whether the local plastic flow property influenced by pre-cracks could influence the prediction results.

Chapter 5 considered an application of shallow crack effect to a typical case of plastic strain localization enhanced by the hydrogen. Hydrogen embrittlement (HE) is widely believed to be harmful to engineering structures made of ferritic steel, particularly in the presence of pre-cracks. This chapter proved the effectiveness of the shallow crack effect when the characteristic of plastic strain localization is changed. Additionally, this effect calls into question the general applicability of conventional investigation of HE susceptibility that mainly focuses on the variation of fracture characteristic, which is often defaulted to cause changes in mechanical properties. Hence, HE susceptibility is deduced to geometric HE susceptibility for shallow pre-cracked structures, while that for deep pre-cracked structures is metallurgic HE susceptibility.

Chapter 6 summarized the results and proposed the outlook.