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Ductile failure prediction of thin notched aluminum plates subjected to combined tension-shear loading

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ABSTRACT

The main goal of the present research is to check the suitability of the combined Equivalent Material Concept-Averaged Strain Energy Density (ASED) failure criterion, called EMC-ASED, in predicting the load-carrying capacity (LCC) of notched aluminum plates subjected to mixed mode I/II loading. For this purpose, first, a set of experimental results on the LCC of thin V-notched rectangular Al 7075-T6 plates, that fail by large-scale yielding (LSY) regime, are taken from the open literature. Then, Al 7075-T6, which is a ductile material, is equated with an equivalent linear-elastic isotropic material by means of the EMC. Finally, the EMC is linked to the well-known ASED criterion to predict the LCC of the notched Al 7075-T6 plates. It is revealed that the experimental results could successfully be predicted by means of the combined EMC-ASED criterion without requiring complex and time-consuming elastic-plastic failure analyses.

1. Introduction

Notches are extensively used in engineering components and structures, particularly in aero-structures. For instance, one can see wide O-shaped notches in the riveted joints, and U- and blunt V-notches in the access panels. Moreover, a large number of high-strength bolts and screws are normally used in aero-structures for joining two or more members in which the threads appear in blunt V-shape. Although notches are useful from the view point of engineering design, they are prone to the crack initiation as a result of the stress concentration at their neighborhood [1,2]. A notch threats the safety of structure which directly depends on the notch geometry and the material from which the structure is made. A higher level of the stress concentration results in a lower level of the structural safety. If the notched structural component is made of a brittle or quasi-brittle material, sudden fracture will be probable that may result in human and/or finance losses. Therefore, the lowest level of the design reliability is obtained when the structural component is weakened by a notch of great stress concentration and made of a brittle or quasi-brittle material [3–6]. Due to such a weak point of brittle materials (i.e. the sudden fracture), it is usually attempted in design of aero-structures to avoid employing brittle materials, unless otherwise essentially required, e.g. ceramics and graphite materials in high temperature applications, etc.

Unlike brittle and quasi-brittle materials, ductile materials have widespread applications in engineering structures that their static failure is usually gradual and their final fracture takes place in a stable manner [7,8]. Such a failure behavior is mainly due to significant plastic deformations [9,10]. If a notched component is made of a ductile material, it is expected that the crack initiation from the notch border and the crack growth will accompanied by a considerable plastic zone around the notch. The existence of such a significant plastic zone at the notch neighborhood and the slow growth of the likely crack emanating from the notch border increase the chance of detecting the crack before the final rupture and the notched member can be repaired or replaced [11,12]. Moreover, future similar failures can be prevented by means of re-designing the component, etc.

A group of ductile materials with wide applications in aerospace structures are the aluminum alloys, particularly the series 2xxx and 7xxx. A review of the standard tensile stress-strain behavior of the aluminum alloys indicates that they exhibit negligible stain-hardening in the plastic zone such that their behavior in some branches of the mechanical engineering, e.g. the metal forming, is usually approximated by an ideal elastic-perfectly plastic behavior. The aluminum alloys Al 2024-Txxx and Al 7075-Txxx, where the index Txxx refers to the type of heat treatment, are extensively utilized in aero-structures and normally weakened by

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notches of various features, e.g. O-, U-, V-, blunt V- and key-hole notches. Considering that the safety of structure is vital in air vehicles, especially in manned vehicles like the civil airplanes, etc., it is necessary to strictly evaluate the resistance of the aero-aluminum alloys against crack initiation from the notch border, so-called the notch fracture toughness (NFT), experimentally and/or theoretically [13–17]. A literature survey indicates that the number of researches on static failure of notched aluminum alloys is very limited and they have been mostly performed in recent years. Like the fracture researches on cracked bodies [18–20], the researches on notched members have also been started with the studies on pure mode I (i.e. the opening mode) loading conditions. Two valuable research works have been recently published on static failure of notched aluminum specimens in which the tensile load-carrying capacity (LCC) of the specimens has been evaluated experimentally and theoretically. In the first work, static failure of the well-known compact-tension (CT) specimens weakened by U-notches of various tip radii and made of Al 7075-T651 has been experimentally investigated, and the mode I NFT has been measured [21]. To predict the experimentally obtained NFT values, the theory of critical distances (TCD) [22–25], which is a well-known brittle fracture theory, has been successfully employed [21]. In the second work, Vratnica et al. [26] have carried out several fracture experiments on the single-edge-notched-bend (SENB) specimens made of commercial aluminum alloy and weakened by U-notches of various tip radii under mode I loading conditions. They have experimentally measured the mode I NFT of the aluminum alloy and successfully predicted the corresponding experimental values by means of a fracture criterion. While both Madrazo et al. [21] and Vratnica et al. [26] have reported good agreement between the experimental and theoretical results, using only the linear-elastic stress distributions around the notch in the theoretical predictions and disregarding the effects of the plastic region at the notch neighborhood on static strength of the aluminum specimens could be questionable. Such a disregard could be justified by Madrazo et al. because of the relatively large thickness of the specimens, while in Ref. [21] the specimen thickness has not been large enough, providing considerable plastic deformations around the notch at the onset of crack initiation from the notch tip.

Recently, Torabi and co-researchers [27–29] have published three papers in which ductile failure of notched aluminum plates under pure mode I loading conditions has been investigated experimentally and theoretically. In Torabi et al. [27] the tensile load-carrying capacity (LCC) of thin rectangular plates made of Al 7075-T6 and weakened by blunt V-notches has been experimentally measured and the corresponding LCCs have been successfully predicted by using the Equivalent Material Concept (EMC) in conjunction with two stress-based brittle fracture criteria in the context of the linear elastic notch fracture mechanics (LENFM), namely the point-stress (PS) and mean-stress (MS) criteria. It has been reported that the V-notched Al 7075-T6 plates fail by the moderate-scale yielding (MSY) regime. A similar work has also been performed by Torabi et al. [28] on the same V-notched specimen, but made of Al 6061-T6 which has been much more ductile than Al 7075-T6. It has been found that the combination of the EMC with the two brittle fracture criteria is also successful in predicting the LCCs of the Al 6061-T6 specimens. The other important finding in Ref. [28] has been that the Al 6061-T6 specimens fail by the large-scale yielding (LSY) regime. By taking into account the results of previous two last given references simultaneously, it can be concluded that the EMC could well be combined with the stress-based brittle fracture criteria for predicting the LCC of V-notched aluminum members regardless of the amount of plastic deformations around the notch at failure. With the aim to study the effects of notch feature (i.e. the notch stress gradient) on suitability of such a combination, Torabi et al. [29] have performed similar assessments on U-notched Al 7075-T6 and Al 6061-T6 plates subjected to tensile loading. The specimen as the same with that studied by Torabi et al. [27,28] containing a U-notch has been employed to conduct ductile fracture tests on Al 7075-T6 and Al 6061-T6. It has been found that like V-notched specimens, the U-notched Al 7075-T6 and Al 6061-T6 specimens fail by the MSY and LSY regimes, respectively. Moreover, the suitability of the combination of the EMC with the two stress-based criteria in predicting the LCC of the U-notched aluminum specimens has been revealed, regardless of the type of the failure regime [29]. Other criteria are available and valid for cracked components but not for the notched components.

Under mixed mode I/II loading conditions, however, the same specimen but with inclined V- and U-shaped notches has been studied in Torabi et al. [6,30,31] for ductile failure. From the experimental point of view, the main difference between the mode I and mixed mode I/II results has been that the entire V- and U-notched aluminum specimens fail by the LSY regime under mixed mode loading, probably because of the significant contribution of shear deformations in forming the plastic zone around the notch at failure. In the theoretical predictions of the LCC, it has been revealed that the EMC could well be combined with the maximum tangential stress (MTS) and mean-stress (MS) brittle fracture criteria [6,30,31].

The literature review reveals that a paper has been published on ductile failure of aluminum alloys containing notches under pure mode II loading [32]. Ghahremaninezhad et al. [32] studied experimentally the crack nucleation from the border of a V-notch in Al 6061-T6 under pure in-plane shear loading. The well-known Arcan specimen configuration was utilized to produce pure mode II loading conditions around the V-notch. The experiments were simulated by means of the Johnson–Cook model and its modified version and it was found that it is essential to account for great levels of the local strain prior to the crack initiation for capturing the large plastic deformations observed in the fracture tests. Some valuable microscopic studied were also performed using the scanning electron microscope (SEM) in order to determine the sites of crack nucleation, etc. [32].

In the present research, it is tried to check the suitability of the EMC-ASED criterion also for mixed mode I/II loading conditions under which the failure regime tends from the MSY to LSY due to significant plastic zone around the notch at failure as a result of large shear deformations. For this purpose, the EMC-ASED criterion is described and formulated in forthcoming sections and the experimentally obtained LCCs reported in Ref. [33] are predicted. A very good agreement is shown to exist between the experimental results and the theoretical predictions, demonstrating that the suitability of the EMC-ASED criterion is independent of the ductile failure regime and the mode of in-plane loading.

2. Fracture test results on notched aluminum plates reported in the literature

A set of mixed mode I/II ductile fracture test results have been recently published by Torabi et al. [33] on thin Al 7075-T6 plates weakened by blunt V-shaped notches. The chemical composition and the mechanical properties of the tested material are presented in Tables 1 and 2, respectively. Moreover, the standard tensile engineering and true stress-strain curves of the material are represented in Fig. 1, from which it is evident that the tested Al 7075-T6 is a ductile material and shows negligible strain-hardening in the plastic zone [33]

In Torabi et al. [33] a rectangular plate of 2 mm thick weakened by a central rhombic slit with four blunt V-shaped corners has been considered for conducting the mixed mode I/II fracture exper-

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