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Research on damage evolution in thick steel plates

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ABSTRACT

This paper reports on the modeling of damage evolution in thick steel plates under load with a continuum damage model proposed by Lemaitre (1985). A constitutive elastic-plastic-damage model was implemented in ABAQUS for the analysis. A set of material tests, including monotonic and repeated tensile tests, were conducted to obtain the mechanical parameters of Grade Q345C steel in 120 mm and 100 mm thick plates. The mechanical properties of material in different directions (horizontal and through-thickness directions) and locations (outer surface, 1/4 thickness and mid-depth) were investigated. Since the numerical load-displacement curves are not matching the experimental curves, a criterion for improving the numerical curves is proposed, and the corresponding damage parameters in the numerical model were also updated. The final improved numerical curves have a good agreement with the experimental results when the updated parameters are included in the analysis. Results show that material close to the outer surface of thick steel plate seems to have better ductility than that near the center indicating that more damage may have occurred during the loading process at mid-depth of the thick plates than near the surface. Damage parameters at mid-depth and in the *Z*-direction (through-thickness direction) are quite different from those at the outer surface and at 1/4 thickness.

1. Introduction

Components fabricated from thick steel plates have been extensively used in high-rise buildings, long-span roof structures and bridges. Thick steel plates are commonly found in box-columns or H-shape columns in structures with thickness ranging from 40 mm to 130 mm [1]. In the main structure of the National Stadium (Bird's Nest), a large amount of Q345GJ-D steel plates were used as column bases, fabricated columns and the main trusses. The mean thickness of plate was bigger than 36 mm and the maximum thickness was close to 100 mm [2]. The thickness of steel plate in the main structure of the China Central Television Tower varies from 40 mm to 130 mm in single-box, twin-box and *D*-box sections [3,4].

When the thickness of a plate is larger than a threshold, its mechanical properties would be different from that of a thin one. Existing researches [1,5–7] indicated that the toughness and mechanical properties are different at different positions of a given plate (e.g. toughness at mid-depth is lower than that at 1/4 thickness) and properties in the through-thickness direction (*Z*-direction) decrease with the plate thickness. The thickness of plate studied ranges from 25 mm to 150 mm. The effect of welding residual stress on thick steel plate was also discussed [8–10]. But most of the articles focused on the numerical simulation of residual stress, and the growth of micro-crack in thick plates has not been studied.

The processes of smelting, rolling, machining and welding for thick steel plates are more complicated than those in thin plates. When steel solidifies, liquid steel may cool unevenly and the solidification process at different locations of plate may be different [11] owing to the large thickness. This leads to segregation, which means the coalescence of inclusion such as sulphides and nitrides is not uniform in the steel plate. Alloy elements such as carbon, phosphorus, sulphur, and manganese coalescence towards the center of the thick plate, causing the formation of a central segregation region [12,13]. This is a catastrophic defect in thick steel plates. In the rolling and machining processes, non-metallic inclusions in the central segregation region are pressed into thin sheets or strips with stratification, which reduces the tensile properties in the *Z*-direction and leads to lamellar tearing [1]. When tension occurs in the *Z*-direction of the plate, micro-cracks initiate close to the inclusions and they extend in the direction parallel to the sheets or strips, ending up with the formation of macro crack [14], as shown in Fig. 1. In the welding process, there is a complicated residual stress field in thick steel plate due to multi-pass welding and unevenly cooling. Examples are in the cruciform and *T*-shape welding joints [1], where the tensile stresses in *Z*-direction provide a suitable stress field for fracture.

Fracture in thick steel plates can be seen as a kind of damage evolution. McClintock [15] and Rice and Tracey [16] explained that micro-cavities in ductile materials become macroscopic with their nucleation,

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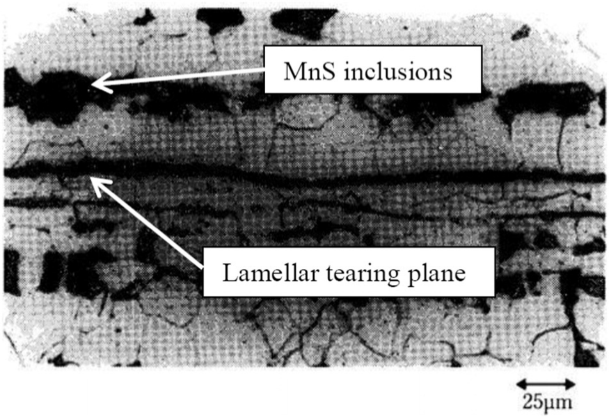

Fig. 1. Non-metallic inclusion in lamellar tearing plane [14].

growth and coalescence. Kachanov [17] introduced a variable D to describe damage in material due to creep. Parameter D ranges from null to unity with null represents the virgin material without damage and unity represents the failure of material. Lemaitre and Chaboche [18, 19] established the Continuum Damage Mechanics (CDM) model with an extended damage concept. In the CDM framework, a ductile damage model was proposed and extensively applied [20–22]. Following the initial framework of Lemaitre's model, several other damage models, based on different damage dissipation potential were developed with a higher accuracy of prediction [23–25]. But most of them were specific for particular kinds of material, and it is more difficult to determine the large number of parameters involved. Lemaitre's model was therefore popularly used in practice.

In this paper, Lemaitre's damage model was used to describe the damage evolution in thick plate. Parameters in the model need to be determined from experiments. Therefore, a set of material tests were conducted to calibrate the damage parameters. This paper is organized as follows: In Section 2, the elastic-plastic constitutive law is introduced in the damage model and coded through the User-defined Material subroutine (UMAT) of ABAQUS. In Section 3, a special experimental program on 100 mm and 120 mm thick Q345C steel plates is conducted. Mechanical properties in horizontal direction and Z-direction at different locations of the thick plates are investigated with discussions on the different sets of material properties obtained. Load-displacement curves of standard sample in monotonic tensile tests are corrected to reduce the effect of slippage. In Section 4, parameters required in the damage model are obtained through repeated tensile tests and they are validated with the corrected load-displacement curves. Monotonic tensile tests are simulated in ABAQUS by inputting the obtained parameters to UMAT. Numerical load-displacement curves are compared with the experimental ones to validate the damage parameters. Since there are three different experimental curves in one group of tests, a unified criterion is proposed to improve the

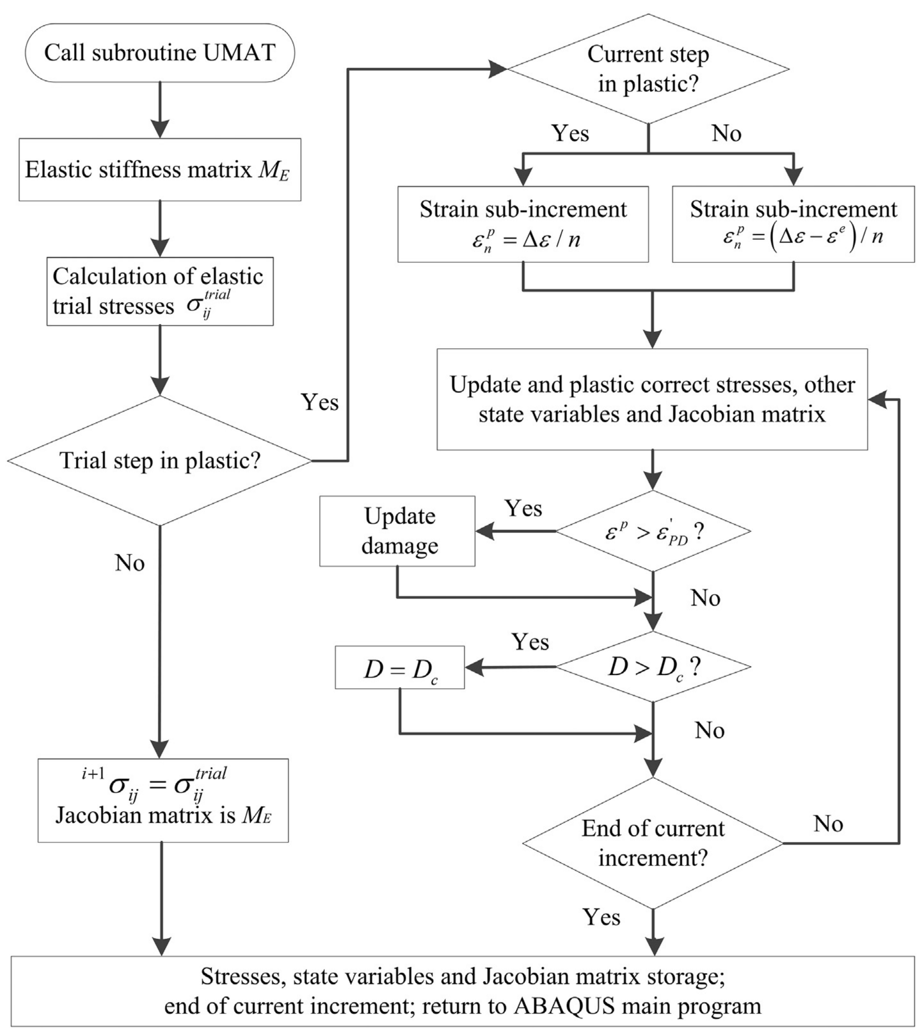

Fig. 2. Flow chart of subroutine UMAT.