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IMPLEMENTATION OF MATERIAL MODEL IN ABAQUS/STANDARD USING UMAT SUBROUTINE

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Abstract

Corrosion-induced material loss can lead to significant degradation of the mechanical properties and load-bearing capacity of steel structural elements. The resulting material behaviour can be associated with the mechanisms of void nucleation, growth and coalescence characteristic of ductile fracture. This paper presents the implementation of a material damage model based on the Complete Gurson Model (CGM) in Abaqus/Standard using a user-defined UMAT subroutine. The implemented model incorporates the Gurson–Tvergaard–Needleman approach and the Thomason failure criterion, enabling the simulation of material degradation and ductile fracture. The input material parameters and state variables required for the numerical analysis are presented, together with the interaction procedure between Abaqus and the UMAT subroutine. The proposed implementation provides an extended material model for numerical analysis of steel elements affected by corrosion and other surface damage mechanisms.

***Keywords**: corrosion, steel, ductile fracture, Complete Gurson Model, UMAT, Abaqus/Standard, material damage*

1. INTRODUCTION

Corrosion is one of the most important degradation mechanisms affecting the durability and load-bearing capacity of steel structural elements. In addition to the reduction of the cross-sectional area, local corrosion damage can significantly influence the mechanical response and failure behaviour of steel. From a modelling point of view, the degradation of material properties caused by corrosion can be associated with damage mechanisms similar to those observed in ductile materials, where the nucleation, growth and coalescence of spherical voids precede final fracture.

The first constitutive model developed to account for the influence of microscopic damage on the load-bearing capacity of a material was proposed by Gurson [1]. Tvergaard subsequently modified the Gurson model to account for the interaction between microscopic voids [2,3]. Tvergaard and Needleman further modified the Gurson yield criterion to describe the rapid loss of load-bearing capacity associated with the coalescence of voids [4]. Zhang and co-workers introduced a significant modification of

the Gurson–Tvergaard–Needleman (GTN) model by incorporating the Thomason failure criterion, resulting in the so-called Complete Gurson Model (CGM) [5].

Within the CGM, the critical value of the damage parameter is determined during the numerical analysis based on the plastic limit load in the ligaments between neighbouring voids. The approach was subsequently extended to materials containing surface damage, such as that caused by localised corrosion. This extension makes the model suitable for numerical investigation of structural elements in which local material degradation plays an important role in the failure process.

The implementation of such a constitutive model in a finite element analysis requires the use of a user-defined material formulation, since the corresponding constitutive equations and failure criteria are not directly available in the standard Abaqus material library. The objective of this paper is therefore to present the implementation of the extended CGM damage model in Abaqus/Standard using the UMAT user subroutine and to define the material input parameters and state variables required for its application.

2. COMPLETE GURSON MODEL (GTN)

The Gurson model describes the behaviour of porous ductile materials by taking into account the influence of microscopic voids on the yield behaviour of the material [1]. The model was subsequently modified by Tvergaard to account for void interaction [2,3], while Tvergaard and Needleman introduced additional modifications to describe the accelerated loss of load-bearing capacity during void coalescence [4].

A further development was proposed by Zhang and Niemi, who incorporated the Thomason criterion into the GTN formulation [5]. This formulation is known as the Complete Gurson Model. The CGM enables the critical damage parameter to be determined during the numerical analysis based on the plastic limit load in the material ligaments between voids.

The use of the Thomason failure criterion provides an improved description of the transition from distributed material damage to localised fracture. This is particularly relevant for the analysis of steel elements subjected to localised corrosion, where the reduction of the material cross-section and the development of local damage can contribute to premature failure.

For the present numerical implementation, the CGM parameters are determined through a combination of experimental investigations and calibration of the model parameters. The relevant Gurson constants, together with the material parameters describing plastic hardening, are introduced into the Abaqus model and subsequently transferred to the UMAT subroutine.

3. IMPLEMENTATION OF THE MATERIAL MODEL USING UMAT

One of the main difficulties in applying the Complete Gurson Model within the finite element method is that the required failure criteria, yield conditions and constitutive equations are not included in the standard Abaqus material library. Abaqus/Standard provides the UMAT interface, which enables users to implement constitutive models developed for specific materials and problems that cannot be adequately described using the available built-in material models [6].

The UMAT subroutine [7-10] defines the local mechanical response of the material and is called by Abaqus during the numerical solution procedure. At each load increment, the

stresses and internal state variables are updated until a converged solution is obtained. The interaction between Abaqus/Standard and the UMAT subroutine is schematically presented in Fig. 1.

Before implementing the UMAT subroutine, the constitutive equations must be explicitly defined, the dependence of the relevant variables on the loading process must be established, and the internal state variables must be defined. Two groups of parameters are particularly important for the implementation: the material properties (PROPS) and the state variables (STATEV).

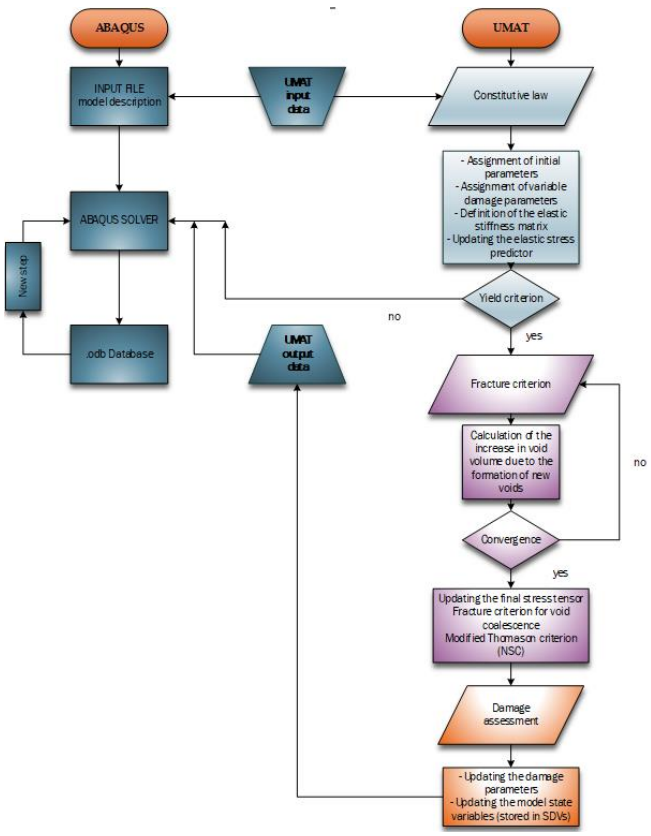


Figure 1. *Schematic diagram of the interaction between Abaqus/Standard and the UMAT subroutine [10]*

3.1. Material input parameters

The input variables required by the UMAT subroutine are listed in Table 1. They include an identification parameter for the selected failure criterion, the initial and nucleated void volume fractions, the parameter defining the initial void size distribution, the hardening exponent, Young's modulus, Poisson's ratio and the experimental true stress–true strain curve.

The Gurson parameters are determined using experimental investigations and calibration. Parameters PROPS(2)–PROPS(5) correspond to the material damage parameters, while the hardening exponent is introduced through PROPS(5). When the Thomason failure criterion is applied, the critical void volume fraction, Fc, does not need to be prescribed in advance. Instead, it is determined during the numerical analysis for each defined time increment.

Table 1. *Input variables used in the UMAT subroutine*

Input variable	Description
PROPS(1)	Identification parameter depending on the selected criterion: Fc or NCS criterion
PROPS(2)	Initial void volume fraction, F_0
PROPS(3)	Void nucleation parameter, F_N
PROPS(4)	Initial void size parameter, A_0
PROPS(5)	n-exponent defining the material hardening behavior
PROPS(6)	Critical void volume fraction, Fc
PROPS(7)	Young's modulus, E
PROPS(8)	Poisson's ratio, ν
PROPS(9)	Number of point pairs on the true stress–true strain curve, NP
PROPS(10,11… 2*NP-1,2*NP)	Pairs of points defining the true stress–true strain curve

The true stress–true strain curve is introduced through a series of point pairs. This enables the UMAT subroutine to reproduce the experimentally determined plastic response of the material rather than relying solely on a simplified analytical hardening law.

3.2. State variables

The state variables are updated during every increment of the numerical analysis. They describe the current mechanical and damage state of the material and provide information about the development of ductile damage and fracture.

Table 2. *State variables used in the UMAT subroutine*

State variable	Description
STATEV(1)	Equivalent plastic strain of the material matrix
STATEV(2)	Void volume fraction at the end of the increment
STATEV(3)	Stress triaxiality
STATEV(4)	Fracture control parameter
STATEV(5)	Plastic strain at the beginning of loading
STATEV(6)	Current value of the control parameter

The fourth state variable is used as a fracture control parameter. When (F < Fc), STATEV(4) is equal to zero and fracture does not occur. When (F=Fc), STATEV(4) takes the value (Fc), indicating the stage before void coalescence. When (F > Fc), STATEV(4) becomes negative, indicating the occurrence of total fracture.

The state variables can be requested as output variables in Abaqus and used to evaluate the spatial and temporal development of material damage during the numerical analysis.

4. NUMERICAL ANALYSIS

The implemented material model is intended for numerical analysis of steel elements subjected to material degradation caused by corrosion [10]. The numerical procedure is based on the use of Abaqus/Standard with the user-defined UMAT subroutine. The subroutine enables the constitutive response of the material and the evolution of damage to be evaluated at each integration point of the finite element model.

Three main steps are required for the application of the UMAT formulation in Abaqus/CAE:

1. definition of the user material properties;
2. definition of the analysis job and its connection with the UMAT subroutine; and
3. selection and visualisation of the SDV variables obtained from the subroutine.

During the analysis, Abaqus provides the current strain increment and state of the material to the UMAT subroutine. The subroutine calculates the corresponding stresses and updates the internal state variables. The updated variables are then returned to Abaqus/Standard and used in the subsequent solution increment.

The numerical analysis therefore enables the evolution of both the conventional mechanical response and the internal damage parameters to be monitored. In addition to the usual output quantities, such as specimen displacement, applied force and von Mises stress, the SDV variables defined in Table 2 can be used to investigate the development of damage and the transition towards fracture.

The force–displacement response obtained from the numerical model can be compared with experimental results in order to evaluate the ability of the implemented model to reproduce the behaviour of degraded steel elements. Particular attention can be given to the development of the void volume fraction, stress triaxiality and fracture control parameter, since these variables provide information about the initiation and progression of ductile fracture.

5. CONCLUSION

The material damage model based on the Complete Gurson Model was implemented in Abaqus/Standard using a user-defined UMAT subroutine. The implementation extends the standard material capabilities of Abaqus by introducing constitutive equations and failure criteria required for the analysis of ductile damage and fracture.

The CGM formulation combines the Gurson model with the modifications introduced by Tvergaard and Needleman and incorporates the Thomason failure

criterion. The resulting approach enables the evolution of material damage to be followed through internal state variables during the finite element analysis.

The implemented UMAT requires the definition of material properties, Gurson model parameters and the true stress–true strain relationship. The state variables provide additional information about plastic deformation, void growth, stress triaxiality and the development of fracture.

The proposed implementation represents a suitable numerical framework for the analysis of steel elements affected by localised material degradation. In particular, the possibility of monitoring the evolution of the damage variables provides an additional tool for analysing the initiation and progression of fracture in corrosion-damaged steel elements.

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