Evaluation of Cryogenic Fracture Performance of Insulation Panel in LNG Carrier using Computational Method

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Abstract: - This article proposes a methodology to evaluate the fracture performance using finite element analysis based on viscoplastic-damage model. The model is implemented to the commercial FEA code ABAQUS user defined subroutine UMAT. For validation, the primary barrier of the Liquefied Natural Gas carrier insulation system which comprises austenitic stainless steel 304L is assessed the fracture performance by experiment and simulation. Fracture test is carried out with respect to the double-edge-cracked tension (DECT) and the center-cracked tension (CCT) specimens at ambient temperature and cryogenic. Obtained simulation results are compared with experimental results and comparison results show overall good agreements. Advantages in the use of the proposed method for assessment of practical structural fracture performance are discussed.

Key-Words: -Cryogenic fracture performance, Damage mechanics, Finite element analysis, ABAQUS user-defined material (UMAT) subroutine, LNG Insulation System, Austenitic stainless steel

1 Introduction

The attempt to simulate the fracture test has been going on animatedly. Although fracture toughness is known as material property and conventionally obtained by experiment, computational methods provide advantages such as costs and times in view of industry fields. Moreover, computational methods can be applied as supporting and alternative tools decreasing efforts to obtain fracture toughness under laborious condition for set up of experiments such as high/cryogenic temperatures, high pressure and various loading condition. Bezensek and Hancock (2007) computationally evaluate fracture toughness on high and low constraint mode I and mixed mode I and II for laser welded joints. Fracture toughness is obtained computationally for each part of base metal, HAZ (Heat Affected Zone) and weld metal, based on these results, local approach model for problem of the strength and toughness mismatch between the weld and the parent plate is proposed [1]. González and LLorca (2007) perform virtual fracture tests of composite materials using multiscale finite element simulations and the fracture behavior was modeled for fiber-reinforced composite beam in presence of a notch in three dimensions using an embedded cell approach that the damage and fracture micromechanisms which control the onset of fracture are included in the behavior as governing parameters. The maximum load is carried out at 25°C, 200°C and 400°C, and the apparent fracture toughness is computed from the maximum load and the initial notch length in the simulations. Simulation results are compared with experimental data, thereby showing the potential of proposed approach to carry out virtual tests to predict the fracture behavior of novel microstructures and materials [2].

However, in those studies, computational fracture toughness test is used as validation data for proposed model and assistant tools for the experimental test, thus application to structural design stage is limited. Moreover, the resistance against crack propagation is usually obtained, though qualitative results such as the direction of crack propagation and failure modes after fracture are hard to evaluate and studies are performed scarcely at high/low/cryogenic temperatures.

Thus, in the present study, computational approach is conducted to evaluate the fracture performance that ensures supporting of robust structure design. Based on the computational approach, it is possible to easily obtain the fracture performance as well as qualitative results such as cracking path by computational approach based on viscoplastic-
damage model. If the stress-strain behavior of material is known, the aforementioned approach can be simply conducted. In addition, it is possible to evaluate the fracture performance under various loading condition and/or extreme environment such as high/low/cryogenic temperatures.

Example of this approach, fracture performance of austenitic stainless steel (ASS) 304L which composes primary barrier of insulation system used in Liquefied Natural Gas (LNG) carrier’s Cargo Containment System (CCS) is evaluated at ambient temperatures. This LNG insulation barrier is undergone variety of loading such as sloshing impact, under cryogenic environment. Therefore, assessments of fracture performance of this insulation barrier are indispensable, though these assessments are confronted with aforementioned problems. Moreover, ASS represents extremely nonlinear material behaviors at cryogenic temperatures. These are caused by the strain-induced martensitic transformation [3]. Thus, general concept of fracture mechanism is limited to assess the fracture performance of the ASS at cryogenic temperature.

Hence, in the present study, the computational approach is proposed for the austenitic stainless steel 304L. Viscoplastic-damage model for ASS 304L proposed in author’s previous study is formulated according to the finite element for implementation to the ABAQUS user defined material subroutine (UMAT), which provides the user-friendly analysis environment. Then, computational fracture toughness tests for LNG insulation barrier are carried out with aforementioned user defined subroutine at ambient temperatures. Although fracture toughness test isn’t conducted at cryogenic temperature, it is also can be obtained based on proposed method including the stress-strain relationship at cryogenic temperature. Obtained results of the simulation are validated with the experimental results for identification of proposed approach’s usefulness and compatibility.

2 Viscoplastic-Damage Model and Implementation to ABAQUS UMAT

The In the present study, a modified Tomita-Iwamoto [4] and Bodner-Partom [5] models was adopted in order to consider the dependencies of the temperature and strain rate of the austenitic stainless steel at various temperatures.

The viscoplastic-damage model including the proposed model which was developed in author’s previous studies [3] can be written as:

\[ \dot{\varepsilon}^a = (1 - f^a)(A\varepsilon^p + B\dot{\varepsilon})H(e^p - e^\text{init}) \]  \hspace{1cm} (1)

\[ Z_i = Z_a + (Z_m-Z_a)f_i \]  \hspace{1cm} (2)

\[ \dot{\varepsilon}^p_{ij} = D_0 \exp \left[-\frac{1}{2} \left( \frac{Z(1-\omega)}{\sigma_{\text{eff}}} \right)^2 \right] \sqrt{S_{ij}} \]  \hspace{1cm} (3)

\[ \dot{\omega} = \frac{b}{h} \ln \left( \frac{1}{\omega} \right)^{\frac{b+1}{b}} \omega \dot{Q} \]  \hspace{1cm} (4)

\[ Q = (C_1\sigma_{\text{max}}^\text{eff} + C_2\sigma_{\text{eff}} + C_3\Gamma_1^\text{eff})^r \]  \hspace{1cm} (5)

\[ Z = Z_i - (Z_i-Z_0)\exp(-mW_p) \]  \hspace{1cm} (6)

\[ W_p = \int dW_p = \int \sigma_i \varepsilon_i \]  \hspace{1cm} (7)

where \( \dot{\varepsilon}^p_{ij} \) is the plastic strain rate, \( D_0 \) is the assumed maximum plastic strain rate, \( Z \) is the total hardening variable, \( n \) is the material parameter that controls rate sensitivity.

\( Z_0 \) and \( Z_i \) are the initial and saturated values of the isotropic hardening variable, respectively, \( m \) is the rate of isotropic hardening and \( W_p \) is the plastic work.

\( b \) and \( h \) are the material parameters that control the features of creep damage developments, and \( \dot{Q} \) is the multi-axial stress function proposed by Hayhurst [6]. \( \sigma_{\text{max}}^\text{eff} \), \( \sigma_{\text{eff}} \), and \( \Gamma_1^\text{eff} \) are the maximum tensile principal stress, effective stress, and first stress invariant, respectively. \( C_1 \), \( C_2 \), \( C_3 \) and \( \Gamma \) are the material constants and are related by the expression \( C_1 + C_2 + C_3 = 1 \).

The aforementioned viscoplastic-damage model is formulated as a discretized formula in order to construct the ABAQUS UMAT. In the present study, the algorithmic tangential stiffness (ATS) tensor is used in stress update algorithm. The specific derivation of the ATS tensor can be identified in the authors’ previous papers [7].

Fig. 1 shows the algorithm of the UMAT calculation.

3 Validation of Proposed Method

3.1 Fracture performance test: experiment

As mentioned previously, the fracture toughness tests of LNG CCS insulation panel are performed. These tests are carried out for two types that are double-edge-cracked tension (DECT) and center-cracked tension (CCT) specimens. In order to vali-
date, the proposed computational method, experimental test results are compared with numerical results. Detailed information of experimental fracture toughness test is given in Ref. [8].

### 3.1.1 Test specimen description

Fig. 2 shows the geometry of the test specimens, based on ASTM standards [9]. Fig. 3 shows the details of the notches and the initial crack in the specimens. The specific geometries of the notches were fabricated according to relevant guides [9]. As shown in Fig. 3, the tip radius of the crack was 0.1 mm and the initial crack length \( a_0 \) was 20 mm. The ratio of the initial crack length to the specimen width (\( a_0 / W \)) was 1/6 and the thickness of the specimens was 1.2 mm. The specimen thickness was determined on the basis of the actual design data of the geometry of an LNG insulation system.

The selected specimen material was austenitic stainless steel (SUS304L), the chemical composition of which is summarized in Table 1.

### 3.1.2 Experimental setup

Fig. 4 shows the experimental apparatus. Servo-hydraulic testing machines with maximum load capacity of ±50 ton (IST-8800 and IMT-8803) were used. To maintain the cryogenic temperature, a special purpose cryogenic chamber was fabricated and installed in the first testing machine (IST-8800; see Fig. 4).

All the tests were terminated at the point where through-width fracture occurred (see Fig. 7). A displacement control mode was used with a constant loading rate of 1 mm/min.

### 3.1.3 Fracture toughness and stress-crack length relationship

In the framework of linear elastic fracture mechanics, fracture toughness can be characterized by the critical strain energy release rate \( G_{IC} \). The formulae for evaluating the fracture toughness of the tension specimens are as follows [9]:

For the DECT specimen

\[
G_{IC} = \left( \frac{P^2}{B} \right) \frac{1}{EW} \tan \frac{\pi a}{W} \tag{8}
\]
For the CCT specimen

\[ G_{IC} = \left( \frac{P^2}{B} \right) \frac{1}{E W} \left[ \frac{\tan \frac{\pi a}{W} + 0.1 \sin \frac{2\pi a}{W}}{\pi a} \right] \]  \hspace{1cm} (9)

where \( P \) is the maximum load before fracture, \( B \) is the thickness of the specimen, \( E \) is the Young’s modulus, \( W \) is the breadth of the specimen, and \( a \) is the pre-crack length.

Another important factor commonly used in structural design is the relationship between the applied stress and the allowable crack length. To obtain this relationship, the determined values of the critical strain energy release rate (\( G_{IC} \)) should be converted to the critical stress intensity factor (\( K_{IC} \)), which includes stress and crack length terms as follows [10]:

\[ G_{IC} = \frac{K_{IC}^2}{E} \]  \hspace{1cm} (10)
\[ K_{IC} = \sigma \sqrt{\pi a H} \]  \hspace{1cm} (11)

where, \( \nu \) is the Poisson’s ratio (0.24 for stainless steel 304L), \( E \) is the Young’s modulus, and \( H \) is a correction factor, which can be obtained from the ratio of the crack length to the specimen width (\( 2a / W \)). In this study, the correction factors used were 1.13 for the DECT tension specimen and 1.09 for the CCT specimen [11].

3.3 Comparison of experimental and computational results

Representative simulation results are shown in Fig. 6 for comparison with experimental results. It can be observed that the crack propagation along the crack tip was sufficiently simulated numerically. Moreover, the final fractured shape obtained by simulation was almost identical to that of the experiment.

Fig. 7 is a comparison of the load and displacement relationships obtained from the experimental results and the numerical estimations. The \( G_{IC} \) values of each test are summarized in Table 2. Fig. 8 compares the applied stress and allowable crack length curves of the two tests, for both ambient and cryogenic temperatures. In this study, a systematic approach involving the following steps was used to perform a computational fracture toughness test: (1) Selection of proper constitutive and damage models, (2) Comparison of the experimental results with those of typical material testing (e.g., uniaxial tension), and (3) Development of a user subroutine and applying it to an actual case. If the adopted constitutive and damage models sufficiently describe the material characteristics, this approach can maximize the effectiveness of a user-friendly environment in the commercial FEA code.
4 Conclusion

In this paper, a method for computational assessment of fracture performance using finite element analysis was proposed. This method was based on the viscoplastic-damage model which was implemented to ABAQUS user defined subroutine UMAT. Proposed computational method was verified by comparing the result with experimental fracture toughness test results. Comparing was carried out quantitatively and qualitatively.

- The fracture toughness of SUS304L which composes the LNG insulation system as a primary barrier was evaluated at ambient and cryogenic temperature by experimental test. The cryogenic temperature was set by -163 °C which is a operation temperature of LNG insulation system. In regard to DECT specimen, obtained GIC values at ambient and cryogenic are 61.6 and 149.5 MJ/m², respectively and 57.8 and 132.5 MJ/m² was obtained in regard to CCT specimen at ambient and cryogenic temperature, respectively.

- The relationship of applied stress and allowable crack length were carried out regard to each specimen at both ambient and cryogenic temperature. With this relationship, allowable crack length can be obtained for relevant applied stress. As a design tool, this relationship can be used for structural design.

- Proposed methodology based on the material constitutive model and numerical algorithm was verified by comparing with experimental results. Not only quantitative results such as $G_{IC}$ but also qualitative results such as load-displacement relation and failure mode was compared and comparing results showed good agreement.

- The results carried out in the present study will be used to evaluate the fracture performance under severe condition for experimental setup such as cryogenic temperature as a supporting/alternative design tool.

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