Materials and Design 57 (2014) 26–39

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Numerical model to predict deformation of corrugated austenitic stainless steel sheet under cryogenic temperatures for design of liquefied natural gas insulation system

Jeong-Hyeon Kim, Seul-Kee Kim, Myung-Hyun Kim, Jae-Myung Lee *

Department of Naval Architecture and Ocean Engineering, Pusan National University, 30 Jangjeon-Dong, Geumjeong-Gu, Busan 609-735, Republic of Korea

ARTICLE INFO

Article history:
Received 13 September 2013
Accepted 16 December 2013
Available online 21 December 2013

Keywords:
304L stainless steel
Transformation-induced plasticity
Corrugated steel membrane
Liquefied natural gas insulation system
User-defined subroutine

ABSTRACT

Austenitic stainless steel exhibits nonlinear hardening behavior at low temperature and under various strain rate conditions caused by the phenomenon of transformation-induced plasticity (TRIP). In this study, a uniaxial tensile test for 304L austenitic stainless steel was performed below ambient temperature (−163, −140, −120, −50, and 20 °C) and at strain rates (10^{-4}, 10^{-3}, and 10^{-2} s^{-1}) to identify nonlinear mechanical characteristics. In addition, a viscoplastic damage model was proposed and implemented in a user-defined material subroutine to provide a theoretical explanation of the nonlinear hardening features. The verification was conducted not only by a material-based comparative study involving experimental investigations, but also by a structural application to the corrugated steel membrane of a Mark-III-type cargo containment system for liquefied natural gas. In addition, an accumulated damage contour was represented to predict the failure location by using a continuum damage mechanics approach.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Natural gas (NG) is one of the cleanest alternative fuels. Compared with fossil fuels such as coal and oil, NG contains less smog-producing pollutants (roughly 20–45%) and produces lower greenhouse gas emissions (approximately 5–9%). Because transporting NG by using pipeline infrastructure is costly and impractical, liquefied natural gas (LNG) has received great attention for its ease of transport and storage. LNG is produced by cooling NG at a temperature below −163 °C; this liquefied form takes up to 600 times less space than NG.

Compared with NG, LNG is easier to store and transport to markets around the world by using double-hulled LNG carriers, designed specifically to handle low-temperature environments. The most important characteristics of an LNG carrier are its cargo containment shape, capacity, and insulation system. Although an LNG carrier can be classified as a membrane tank system or an independent tank system, the former has recently been preferred owing to the practical use of cargo containment space. That is, prismatic membrane tanks utilize the hull space more efficiently, occupying less void space than the self-supporting tanks of an independent tank system.

There are two kinds of membrane tanks depending on the main materials and structures used for the insulation system: Mark III and NO96. Although both insulation systems have been adopted in current shipbuilding industries, the Mark III type is preferred owing to its excellent structural strength in comparison to the NO96 tank system, which employs a thin 36% nickel (Invar) steel as the primary and secondary barriers. The volume of an LNG cargo containment system has been increased to more than 260,000 m^3 since the first LNG cargo tank with a capacity of 50,000 m^3 was built in 1971. Fig. 1 shows the Mark-III-type LNG carrier and the inside of an LNG cargo containment system. As shown in the figure, a significant number of corrugated steel membranes are installed at the surface of the LNG cargo containment system. A thin and corrugated 304L stainless steel is adopted as the primary barrier for the Mark-III-type LNG containment system to prevent the repeated thermal deformation resulting from a temperature difference. That is, the primary barrier is contracted and expanded during loading (−163 °C) and unloading (20 °C), respectively, of LNG owing to its temperature difference. In this respect, corrugated steel membranes play important roles from viewpoints of thermal resistance, strength, and elongation properties, and relevant research that targets the first barrier of the insulation system has been reported [1–4]. Research on the pressure resistance, sloshing response, and weldability of corrugated steel membranes has been conducted using various analytical techniques. However, these studies did not investigate nonlinear hardening behavior, which is the main characteristic of austenitic stainless steel that occurs in low-temperature ranges, and did not consider the operating temperature (−163 °C) of LNG corrugations. Prior to structural analysis, material

---

* Corresponding author. Tel.: +82 51510 2342; fax: +82 51512 8836.
E-mail address: jaemlee@pusan.ac.kr (J.-M. Lee).

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.12.037

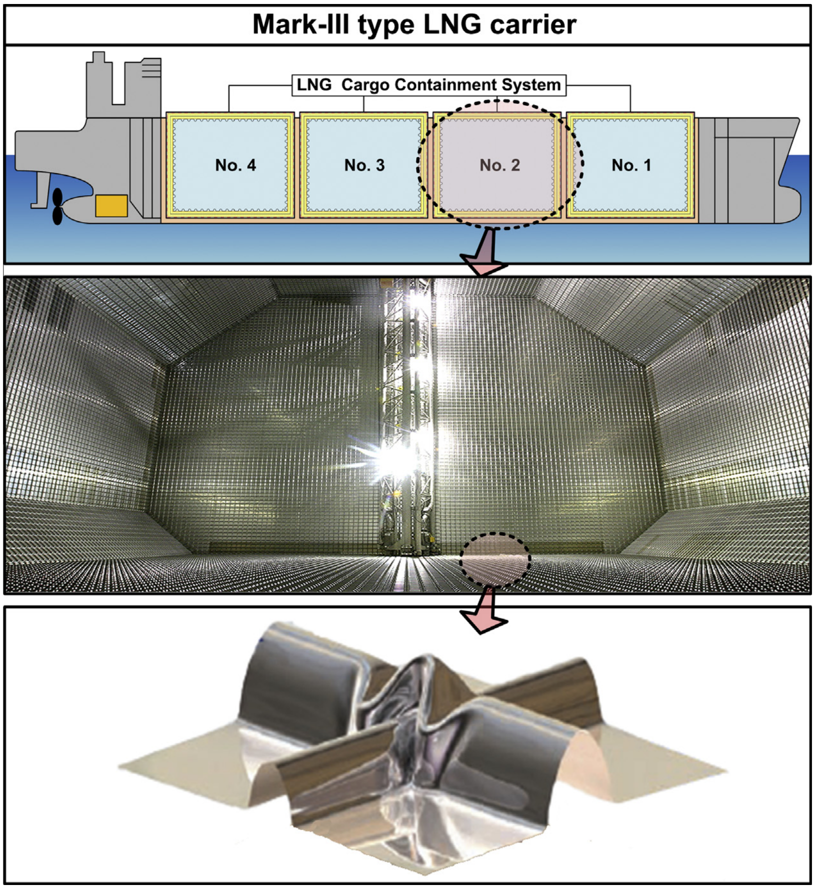

Fig. 1. Mark-III-type LNG carrier and its insulation system: corrugated steel membrane.

investigations should first consider the operating environment of the target structure.

The main material for the corrugated steel membrane of the LNG cargo containment system is 304L austenitic stainless steel. This steel is a transformation-induced plasticity (TRIP) steel that transformed into martensite phase during plastic deformation. This makes it possible to achieve an excellent combination of strength and ductility. This kind of stainless steel is suitable for reinforcement parts and structural components having a complex shape. Therefore, research on this 304L austenitic stainless steel has been extensively reported. The experimental investigation of 304L stainless steel in the context of tension has received wide attention from many researchers. Blandford et al. [5] reported the tensile stress–strain relationship for a 304L stainless steel plate at temperatures ranging from approximately 30–315 °C (i.e., 30, 150, and 315 °C) and a strain rate (1.0 mm/min). They reported that the yield strength, fracture strength, fracture strain, etc., as part of the stress–strain relationship were significantly influenced by the target strain rate and temperature conditions. The testing results of the stress–strain curves were offered for commercial use and verified by comparison with the minimum yield and tensile strength limit of the ASME Code. Lee et al. [6] reported the microstructural evolution of 304L stainless steel and its stress–strain relationship at high temperature (300, 500, and 800 °C) and high strain rates (2000–6000 s^{-1}). Their work revealed that flow stress decreases with increasing temperature but increases with increasing strain rate. The volume fraction of martensite decreases with increasing strain rate and temperature. Lee and Lin [7] reported dynamic behavior in terms of a high strain rate (800–4800 s^{-1}) with and without prestraining at room temperature. The prestrained 304L stainless steel was significantly influenced by the strain; in addition, the strain rate and flow stress increased with the prestrain level. The results of this study also revealed that the flow stress for 304L stainless steel increased under loading conditions from quasi-static to dynamic. Qu et al. [8] studied the tensile and compressive properties of 304L stainless steel and compared them with those of equal channel angular pressed (ECAP) specimens. The results of this study revealed that the yield and fracture strength increased, but the elongation and strain hardening rate for 304L stainless steel decreased after ECAP treatment. Moreover, various studies of 304L stainless steel have addressed not only tensile and mechanical behavior but also high-temperature creep [9–11], low-cycle fatigue [12–14], high-cycle fatigue [15–17], and hydrogen embrittlement [18–20].

These investigations indicate that the mechanical behavior of 304L stainless steel is significantly influenced by the temperature condition. However, the plastic deformation of 304L stainless steel at low temperatures has received less attention. Moreover, very little research has targeted temperature ranges for LNG application (approximately −163 °C).

In this study, constitutive-damage models are also proposed and implemented in user-defined material subroutines to describe the TRIP phenomenon and degradation of material, respectively, on the basis of experimental results. The study of developing or proposing a material model for austenitic stainless steel has been addressed by many researchers. For example, Abed and Voyiadjis [21] proposed two constitutive models of body centered cubic (bcc) and face centered cubic (fcc) metals at high temperatures and high strain rates. They focused on Al-6XN, which is an austenitic stainless steel material that shows a combination of both bcc and fcc

Download English Version:

https://daneshyari.com/en/article/829317

Download Persian Version:

https://daneshyari.com/article/829317

Daneshyari.com