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High temperature strength and multiaxial fatigue life assessment of a tubesheet structure

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ABSTRACT

A continuum damage mechanics (CDM) model was adopted to calculate the multiaxial fatigue damage of perforated structure (also called 'tubesheet') of a heat exchanger. In achieving this goal, the structure strength was numerically investigated in terms of steady and transient state prior to perform fatigue life prediction. Due to the complexity of geometry and loading pattern, the three dimensional (3D) finite element (FE) model was established for the tubesheet, and the changes of the multiaxial factor were explored in the spatial and temporal perspective respectively. Furthermore, the fatigue damage evolution was analyzed by taking multiaxial factor into account. Finally, the results showed that the fatigue damage evolution was significantly accelerated by multiaxial factor, and the life prediction by multiaxial CDM was in good agreement with observed data for the tubesheet.

1. Introduction

Heat exchanger is one of the key components, and the tube-shell type one is widely used in the chemical process, refinery, coal-fired and nuclear industries. Heat exchanger is usually made of the tube, tubesheet and shell structures. In many industrial applications, the tubesheet structure is one of the components that run with the most severe loading. Due to such severe operation conditions and its complicated 3D structure with an arrangement of numerous penetration holes, to design and evaluate a tubesheet structure is a great challenge to the engineers. As indicated in many literature [1,2], tubesheet cracking subjected to cyclic thermal transients is a major failure form for tube-and-shell heat exchangers as shown in Fig. 1. In fact, it is hard to take effective measures to prevent this kind of fatigue failure from happening again. As well known, the increasing operation flexibility requires frequent startup and shutdown for heat exchangers, accordingly, thermal-mechanical transient strength is essential and required to be accurately assessed for the consideration of safety and economy.

In order to achieve the design and evaluation of the thermal transient strength and fatigue damage for the tubesheet, numerous efforts have been made by many researchers and engineers. According to the recent elevated temperature design codes of ASME-NH, RCC-MR and ASME BPVC, the basic approaches in determining fatigue damage are the same as linear damage accumulation (LDA) [3]. The tubesheet structures were designed to formalize codes such as ASME BPVC. However, the 'design by rule' approach needs a number of enhancements to meet future anticipated needs [4]. For instance, a primary waste heat exchanger of material ASTM A 213 grade T11 failed after only three and a half months operation, it revealed that the tubesheet was exposed to frequent thermal cycling and excessive local heating. Through simulated experimentation, it was found that a unique operating environment including elevated temperatures and thermal transients during in-service operation led to thermal fatigue of the

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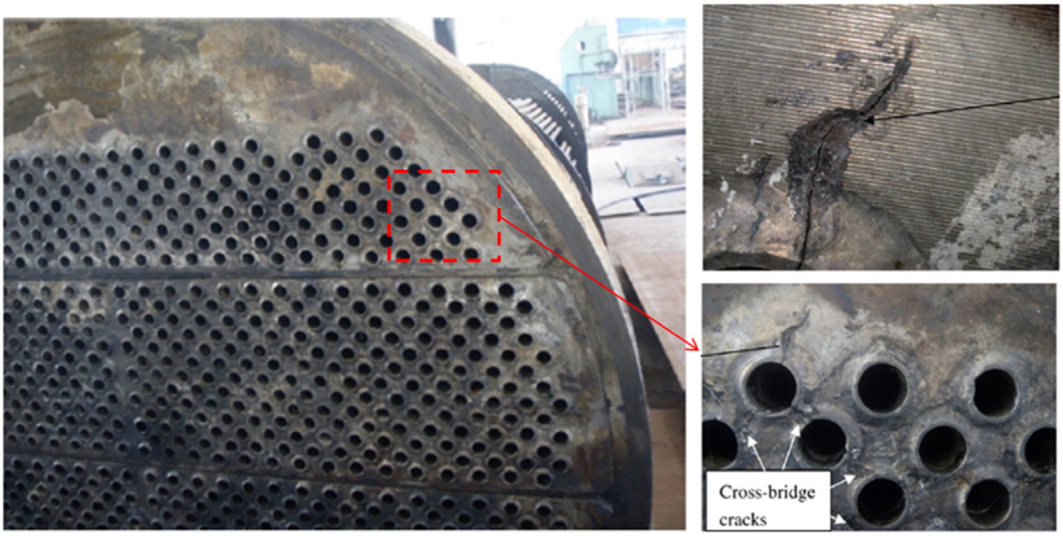

Fig. 1. A real tubesheet out of service due to cracking and many cross-bridge cracks [7].

tubesheet with consequent failure [5]. To clarify the failure mode of a tubesheet, a cyclic thermal loading test was performed for a tubesheet test structure made of modified 9Cr-1Mo steel [6]. Afterwards, the metallographic, fractographic and hardness testing as well as the mathematical root-cause analyses showed that the tubesheet fracture was induced by fatigue cracking. Consequently, cross-bridge cracks were observed after the tubesheet being put into use for only half a year [7]. So far, it could be noted that most of the tubesheet failure was related to thermal fatigue or cyclic severe loadings. In further exploring the fatigue damage, the FEM was considered in numerous analyses. Since the fatigue damage was related and initiated by temperature transients and high local stresses, thermal-elastic-plastic FE calculations were carried out prior to fatigue evaluation [8–10]. The transient temperature and stress fields were analyzed by considering the startup and shutdown operating processes [11]. Owing to complicated structures and loadings, 3D FE analyses were conducted at several critical location of the tubesheet. Shalaby [12] found a maximum stress of 932 MPa in the region of incipient crack, and adoption of the method for design purpose after applying usage safety factor was recommended. However, in-service tubesheet of the heat exchanger sustained complex loading, the multiaxial stress states are unavoidable [13]. Although a number of fatigue life prediction models, e.g. ductility exhaustion model, strain range partitioning model, and frequency modified model had been developed in the past decades [14], these models were usually used to analyze the uniaxial fatigue behaviors. In overcoming the disadvantages of the uniaxial stress and linear damage summation, the multiaxial CDM is highly desirable for investigating the multiaxial fatigue damage of the tubesheet.

Therefore, the major objective of the present study is to numerically investigate the multiaxial fatigue behavior of the tubesheet. Toward this end, a 3D FE model was established for steady and transient fields calculation. A model based on multiaxial CDM was adopted to be compared with the uniaxial one and LDA approach. Through rigorous investigation, the influence of multiaxial stress on fatigue damage was analyzed in depth. Finally, it was found that the fatigue damage predicted by multiaxial CDM agreed with the observed data at the selected location.

2. Mathematical model

For a fatigue process with a strain-controlled cycle, the damage per cycle is defined as [15],

$$D_i = 1 - \frac{(d\sigma/d\varepsilon)_i}{(d\sigma/d\varepsilon)_{N=1}} \tag{1}$$

where $(d\sigma/d\varepsilon)_i$ and $(d\sigma/d\varepsilon)_{N=1}$ are the cyclic modulus and the cyclic modulus at initiation, respectively. Eq. (1) can be obtained through the fatigue experimental measurement of a strain-controlled cycle. Eq. (2) defines the damage D by considering the reduction of the actual structure loading area, which can be explained as the cross-sectional area A_r, divided by effective cross-sectional area A_r^* due to the propagation of micro-cracks or voids. Thus, the fatigue damage may be given as,

$$D = 1 - \frac{A_r^*}{A_r} \tag{2}$$