Journal of Constructional Steel Research 126 (2016) 83–91

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental and numerical studies of the failure of steel jumpers under snag loads

Mengqi Liu *, Francisco Morera, Jason Grisel

T-Rex Engineering + Construction, 16425 Jacintoport Blvd., Houston, TX 77015, USA

ARTICLE INFO

Article history:
Received 31 December 2015
Received in revised form 18 June 2016
Accepted 12 July 2016
Available online xxxx

Keywords:
Local fracture strain criterion
Ductile failure
Steel pipe
Snag load
Finite element analysis

ABSTRACT

To limit damage to subsea equipment caused by snag loads, breakaway joints allow failure locations to be strategically defined in the subsea system. A stress modified critical strain (SMCS) failure criterion is used to model the rupture behavior of a notched rigid subsea jumper made from API X65 steel. The jumper is evaluated using finite element analysis when subject to snag loads applied in a given direction. The criterion measures the plastic strain up to failure as a function of stress triaxiality. To verify the accuracy of the failure model, a full scale experimental snag load test is implemented and the resulting snag load-displacement curve is compared with the corresponding finite element simulation. The finite element simulation is observed to predict the experimental load-displacement curve very well up through crack initiation and full breakage at the notched section. Finally, the validated failure model is used in an extensive parametric study of the notch geometry, and design guidance is proposed for an optimally balanced design when consideration is given to snag, fatigue, and operational loading.

1. Introduction

An accidental snag load may be caused by an anchor from a vessel/rig, trawling equipment, or other fishing gear being dragged across subsea equipment, pipelines, and/or umbilicals. When a pipeline gets snagged, it will be pulled by the anchor until either the mooring chain breaks or the vessel stops. Planning for the mitigation of damage due to snag loads on subsea structures can lower risk by both minimizing potential for snag events (e.g., trawling protection structures) and minimizing damage from snag events (e.g., strategic breakaway joints). Breakaway joints are strategic failure locations that allow specific structures to be protected if surrounding components encounter drag load. In the illustration below, the “jumper” is a steel pipe configured into an “M” shape to allow relative movement between the PLET and Manifold. The breakaway joint is built into the jumper to separate the manifold and PLET/pipeline from snag events; if the pipeline is caught in a snag event, damage will be limited to the jumper. A result of installing the breakaway joint is that additional damage to assets will be prevented.

Different methods have been employed for designing breakaway joints, one of which involves the design of a weak link or location of directed failure. The weak link must be designed to withstand internal pressures, fatigue loads, and other operational loads while also ensuring the snag event will result in failure occurring at the desired location.

To design a weak link that strategically ruptures before other surrounding components, material behavior must be well understood up to complete failure at the section of interest. During the past few decades, failure mechanisms of ductile materials induced by different types of loadings have been widely studied and many damage models have been proposed. To properly represent a damage model for ductile materials, three stages of material failure must be represented: void nucleation, growth and coalescence [1,2]. During the last stage, inter-void matrix necking and local plastic failure are induced which lead to material failure. The rate of void growth was found to be dependent on stress triaxiality and equivalent plastic strain [3,4]; hence, two micromechanical models were developed to predict ductile material fracture. The first model considers material degradation using a constitutive model that is dependent upon microstructural changes due to void growth. The Gurson–Tvergaard–Needleman (GTN) model is based on a representative volume element containing a spherical inclusion at its center and focuses on void volume fractions at critical stages upon which failure initiation depends [5,6]. The second type links the void formation and growth process to macro strains and stresses, also regarded as “damage parameters”. The void growth model (VGM) defines failure equivalent plastic strain as a function of stress triaxiality and integrates the stress function over the strain up to failure [3,7]. Finally, the stress modified critical strain (SMCS) model involves the same integration as proposed by VGM, but also uses a history-independent stress function associated with an assumed constant stress triaxiality along the whole loading process [8]. A shortcoming of the GTN model is that it has nine parameters that must be calibrated. The VGM requires calibration of only three parameters, but the stress-strain curve of the whole deformation history is required. The SMCS model incorporates three unknown material parameters and is based on the instantaneous stress values making it easier to implement. The material parameters were directly solved with simple equations [9]. Subsequently, several numerical approaches and closed-

---

* Corresponding author.
E-mail address: shuailang2004@hotmail.com (M. Liu).

http://dx.doi.org/10.1016/j.jcsr.2016.07.011
0143-974X/

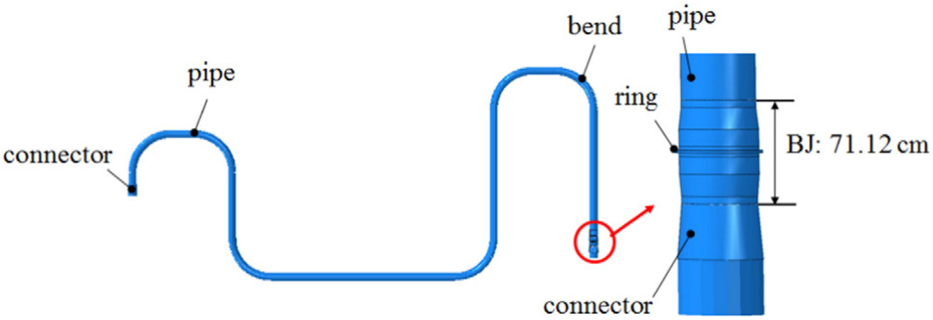

Fig. 1. Geometry of the full jumper system.

form expressions were proposed to evaluate the parameters with more accuracy and the results were verified with experimental data [10–12]. Oh et al. established a ductile failure model for API X65 steel on the basis of the SMCS model by determining the failure strain as a function of stress triaxiality using finite element simulation on notched pipe [13]. The failure model was then applied to predict the burst pressure of notched pipe and the results were found to be in good agreement with the test results [11,14].

The burst pressure of stainless steel pipe subject to combined axial load and internal pressure was studied by Lasebikan and Akisanya [15]. However, there are no existing studies accounting for the notch based steel pipe subject to large bending moments in the pipe. Additionally, limited experimental data could be found to validate the failure model of API X65 steel, and all relating tensile and bending tests were implemented on standard round bar samples rather than pipe cross-sections.

In this paper, the failure behavior of an M-shaped jumper incorporating a Break Away Joint (BAJ) when subject to a snag load is predicted using the local failure model for API X65 steel proposed by Oh et al. [11]. The jumper connects a PLET to a manifold. The BAJ is a notched segment installed near the PLET where the snag load is exerted. The jumper is configured to induce high moments at the BAJ during a snag event. To verify the applicability of this failure model to the BAJ under snag load conditions, a test is conducted whereby the PLET-end of the jumper (including the BAJ) is tested and the results used to validate the finite element simulation.

The rest of the paper is organized as follows. In Section 2, the details of jumper configuration and material properties are given. In Section 3, loading on the jumper is analyzed up to failure based on the SMCS failure model presented above. In addition, a parametric study on the notch geometry is performed to investigate its effect on fracture behavior of the jumper. The failure of a partial jumper model is simulated by using the same failure model and the corresponding test procedure is described in Section 4. In Section 5, the simulation and experimental results of the partial jumper model are compared. The strength of manifold is checked based on the full jumper simulation result and the optimal notch configuration is identified. The paper concludes in Section 6.

2. Breakaway joint (BJ) based jumper system

A M-shaped jumper is planned to be designed and installed to connect a pipeline end terminate to a manifold at a water depth of approximately 4200 ft (Fig. 1). It is composed of 7 straight pipe segments, 6 bends and 2 connectors which attach the jumper to the manifold and the PLET. When the incoming pipe to the manifold gets snagged, the force would accumulate at the manifold end and the manifold could be damaged if the pipeline continues being pulled. Thus, a weak section (breakaway joint) is employed to the jumper to achieve a quick rupture during snagging. The behavior of the BJ based jumper is examined to ensure the manifold performs within its allowable range up to the jumper breakage.

2.1. Jumper configuration and material properties

The jumper pipe has outside diameter $D_0 = 50.80$ cm and wall thickness $t_0 = 2.70$ cm. The horizontal hub-to-hub length is 30.48 m. The outside diameter, wall thickness and length of the connector are $D_c = 58.12$ cm, $t_c = 6.35$ cm and $L_c = 76.20$ cm respectively. At the manifold end, a connector is used to connect jumper and manifold. The PLET is connected to the BJ through a connector including a cone segment with varied thickness to avoid the lateral buckling which may be caused by the abrupt change of section thickness between BJ and the connector (see Fig. 1). The BJ is then attached to jumper. The material of jumper is API 5L X65 and the BJ and connector materials are ASTM A694 F65. The corresponding material properties are obtained from uniaxial tests and listed in Table 1. The engineering and true stress strain curves are shown in Fig. 2. The engineering stress-strain curve is related to the original cross sectional area and length of the specimen and the true stress-strain curve is associated with the deformed area and length at any load of interest. In this research, the engineering stress-strain curve was obtained from uniaxial tensile tests, and the true stress-strain curve was calculated based on the engineering curve by the following equations: $\sigma_t = \sigma_e (1 + \varepsilon_e)$, $\varepsilon_t = \ln(1 + \varepsilon_e)$, where σ_t and ε_t denote for true stress and strain while σ_e and ε_e represent engineering stress and strain.

2.2. Breakaway joint (BJ)

The BJ is 71.12 cm in length and notched at the center. It has constant inside diameter along the longitudinal direction while the wall thickness reduces gradually from the center to both ends (Fig. 3). The left side is connected to jumper and has the same thickness as the pipe. The junction of the BJ and the connector at the PLET side is formed by a transition cone with wall thickness varying from 3.18 cm to 6.35 cm. The notch section has the minimum wall thickness and hence is where breakage is expected to happen.

To expedite the breakage of the BJ, the groove-ring system is developed. A circular ring is placed at the notch with the gap between them initially. When the BJ starts deforming due to the applied load, the ring would finally be pinched by the notch as the bending curvature

Table 1
Mechanical properties of materials of jumper structure.

Material	Young's modulus (GPa)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)	Area reduction (%)	Fracture energy (J/m^2)
ASTM-A694-F65	198	450	557	35	76	7.704
API-5L-X65	207	487	580	29	70	7.704
Ring Material	200	690	–	–	–	–