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Failure pressure prediction of a cracked compressed natural gas (CNG) cylinder using failure assessment diagram

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ABSTRACT

This paper describes two different levels of failure assessment diagram (FAD) to predict the failure pressure of a cracked Type 1 full metal compressed natural gas (CNG) cylinder containing an internal longitudinal surface crack. The fracture toughness and stress–strain curve of the metal are determined by carrying out crack tip opening displacement (CTOD), Charpy impact and tensile coupon tests, respectively. Combining the stress intensity factor (K_I) and reference stress (σ_{ref}), the Level 2A FAD curve is used to predict the failure pressures of 12 cracked CNG cylinders. After then, finite element (FE) mesh models are generated to calculate the elastic and elastic–plastic *J*-integral as well as the plastic collapse load used to construct the Level 3C FAD curve. From the detailed study, it is found that the failure pressures predicted from the Level 2A FAD curve tends to be conservatively safe, and the level of conservatism ranges from 17.7% to 42.2% as compared to the one predicted from the Level 3C FAD curve. In practice, it is safe to use Level 2A FAD curve to predict the failure pressure of a Type 1 full metal cracked CNG cylinder. For convenient purposes, a regressed equation based on Level 3C FAD analysis is proposed to determine the failure pressures of the cracked CNG cylinders.

1. Introduction

Compressed natural gas (CNG) is usually stored and distributed in cylinders. A typical Type 1 full metal CNG cylinder fitted in vehicle shown in Fig. 1 is designed to be filled up to a settled pressure of 200 bar for up to 1000 times per year of service, in a maximum of 20 years of service life (ISO 11439, 2000). When the number of pressure cycles exceeds the service life requirement, sometimes a surface crack may grow from the internal wall. The internal pressure produces hoop and longitudinal stresses at the mid-sidewall of a CNG cylinder, with amplitude of the former twice of the latter. Therefore, the surface crack is most likely to orientate longitudinally. Due to the presence of a surface crack, the hoop stress at the remaining ligament ahead of the crack tip will be amplified. This means that the bearing capacity of the CNG cylinder must be compromised in order to ascertain the safety requirement. The bearing capacity of the CNG cylinder is defined as the allowable maximum internal pressure before leak or rupture occurs. Once the surface crack grows to a certain size, the allowable internal pressure of the cracked CNG cylinder will be lower than the service internal pressure. When this happens, the cracked CNG cylinder is extremely unsafe, resulting in either leak or rupture. As rupture failure of a CNG cylinder can be quite catastrophic, therefore, there is a need to produce a guideline which can be used to predict the failure pressure so as to assess the safety of a defective CNG cylinder.

For the past decades, several research programmes had been carried out to investigate the linear elastic stress intensity factors of cylinders containing surface cracks (Newman and Raju, 1980; Raju and Newman, 1982; Nabavi and Shahani, 2008). Their works focused on pressure vessels rather CNG cylinders taking into account of linear elastic fracture behavior only. However, when assessing the safety and integrity of a cracked CNG cylinder, it is necessary to take into account both linear elastic fracture and fully plastic collapse behavior. In this situation, failure assessment diagram (FAD) approach originally proposed by Dowling and Townley (1975) becomes a wise choice as it is constructed through two separate calculations based on the two extreme behaviors, namely linear elastic fracture and fully plastic collapse. Theoretically, the

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Fig. 1. A 30-L CNG cylinder mounted at the boot of a car.

FAD approach can also be used to predict the failure pressure and assess the safety of a cracked CNG cylinder allowing for the plastic collapse behavior. However, there is a need to verify the usage of the FAD approach on cracked CNG cylinders used in vehicles.

In BS7910 (2005), there is a detailed procedure for assessing metal components or structures containing a crack-like flaw using FAD approach. By using the standard procedures recommended in BS7910 (2005), the failure pressure of a cracked CNG cylinder can be predicted. In this study, a 30-L Type 1 full metal CNG cylinder was cut along the longitudinal direction to reveal its actual profile. Then, standard Charpy impact and crack tip opening displacement (CTOD) tests were carried out to determine the fracture toughness of the steel. After the material fracture toughness is obtained, the standard Level 2A FAD curve specified in BS7910 (2005) is used to predict the failure pressures of 12 cracked CNG cylinders, combining the solutions of stress intensity factor K_I and reference stress σ_{ref}.

As mentioned in BS7910 (2005), the standard Level 2A FAD curve is deemed to be the lower bound. As a result, the predicted failure pressure obtained from Level 2A FAD curve should be lower than the actual result, and hence it is necessary to evaluate the accuracy of the predicted results from Level 2A FAD curve. For predicting the failure pressures of cracked CNG cylinders, it is desirable to carry out destructive tests on these defective CNG cylinders. However, to the authors' knowledge, there are no such experimental test data available in the literature. The main reason may due to the fact that it is impossible to machine cut a semi-elliptical crack shape on the internal wall of a CNG cylinder. In this respect, FE method has become an indispensable tool which can be used to evaluate the predicted failure pressures obtained from Level 2A FAD analysis. In this study, a mesh generator is developed to generate the finite element (FE) models of all the cracked CNG cylinders, for calculating the elastic and elastic–plastic J-integral and the plastic collapse load (P_c). These parameters are then used to construct the Level 3C FAD curve to obtain the failure pressures which are then compared with the Level 2A results. Level 3C FAD curve is constructed fully through numerical results, and it is deemed to produce a more accurate prediction. Therefore, it can be used to compare the accuracy of the predicted results obtained from Level 2A FAD curve. In reality, it is very arduous and time-consuming for engineers to carry out Level 3C FAD analysis as it involves calculating the elastic and elastic–plastic J-integral and the plastic collapse load using FE method. The primary difficulty is from generating the 3D mesh models of the cracked CNG cylinder containing a surface crack. For convenient purposes, a regressed equations based on Level 3C FAD analysis is finally proposed and recommended to predict the failure pressures of the cracked CNG cylinders.

2. Geometries and crack shapes

Using the cross-sectional profile of the 30-L CNG cylinder, a 3D model is created as shown in Fig. 2, with the overall length $l = 824$ mm, external diameter $D = 230$ mm and wall thickness $t = 6.4$ mm.

A surface crack located at the internal wall of a CNG cylinder is discovered occasionally during the periodic inspection and requalification works. Lin and Smith (1998) found that during the crack propagation growth, the internal irregular surface crack front will rapidly approximate a semi-elliptical in shape. Thus, a semi-elliptical internal surface crack shown in Fig. 3 is adopted in the finite element modeling. The assumed surface crack covers a wide range of crack profiles, where the ratio of crack depth to wall thickness a/t ranges from 0.4 to 0.8 with an interval of 0.2 and the ratio of crack depth to crack length c/a ranges from 1.5 to 3 with an interval of 0.5 (Table 1).

3. Material properties

A set of coupon tests were then carried out to determine the stress–strain curve of the steel. All the specimens were cut from the sidewall of the cylinder in the longitudinal direction and fabricated in accordance to the requirements specified by BS EN10002-1 (2001). The true stress–strain curve of the steel is plotted as shown in Fig. 4.

In order to obtain the fracture toughness of the steel, a crack tip opening displacement (CTOD) test was performed in accordance with BS7448-1 (1991). The setup of the three point bending specimens is shown in Fig. 5 where a single notched bend specimen was subjected to an increasing monotonic force. The applied force is plotted against the notch opening displacement as shown in Fig. 6. According to the validity criteria specified in BS EN ISO 12737 (2005), a parameter called F_Q should be evaluated first to decide whether the result obtained from the three point bending test is a plane strain fracture toughness (K_{IC}) or a critical CTOD fracture toughness (δ_C). Fig. 6 shows a line OF_Q drawn using a slope of 95% of the initial slope of force–displacement graph and the force at the intersection point is taken as F_Q. If the ratio of the maximum force F_{max} to F_Q does not exceed 1.10, then test data can be used to calculate K_Q which is an interim value of K_{IC}. It shows that the validity criterion is not met for the determination of plane strain fracture toughness, and hence the test is not a valid K_{IC} test. The test record was subsequently interpreted to obtain a critical CTOD value. The CTOD fracture toughness δ_{IC} is 0.07 mm. The fracture

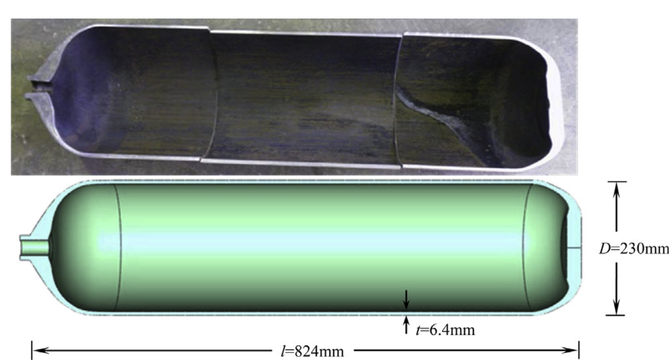

Fig. 2. Cross-sectional view and 3D model of a 30-L CNG cylinder.