Composites: Part A 81 (2016) 129–138

Contents lists available at ScienceDirect

Composites: Part A

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

Strain energy release rate in shaft-loaded blister tests for composite repairs on steel

J.M. Linden [a,b,*], G. Kotsikos [a], A.G. Gibson [a]

[a] School of Mechanical & Systems Engineering, Newcastle University, Stephenson Bldg, Claremont Rd, NE1 7RU Newcastle upon Tyne, United Kingdom
[b] Cooperative Research Centre for Advanced Composite Structures, 1/320 Lorimer Street, Port Melbourne, Victoria 3207, Australia

ARTICLE INFO

Article history:
Received 5 July 2015
Received in revised form 13 October 2015
Accepted 20 October 2015
Available online 4 November 2015

Keywords:
B. Fracture toughness
B. Debonding
B. Interface
D. Mechanical testing

ABSTRACT

The design of composite repairs of corroded oil and gas pipelines must take into account the strength of the interface adhesion between composite and metal. A shaft-loaded blister test is a common method to measure interface fracture toughness and energy release rate. The study aimed on evaluating shaft-loaded blister tests as replacements for more complex pressure blister tests. Specimens investigated were thick fibre-reinforced plates bonded on metal disks as substrates containing a circular through-hole defect. This paper presents the influence of different punch head geometries on the resulting energy release rates and compares the results with blister tests using fluid pressure. Test and simulation results are presented and analytical solutions were derived and evaluated to establish best fitting formulations. It was shown, that significant variations between the different means of loading exist.

1. Introduction

Oil and gas pipelines made from steel are particularly affected by corrosion and erosion as production is often carried out in extremely harsh environments such as the North Sea, the Arabic peninsula or Siberia. Furthermore, transported fluids like crude oil are highly corrosive and erosive themselves and can additionally increase the aggressiveness, due to large temperature gradients between fluids and environment. With design lives of 20 years and more, severe material deterioration of steel pipelines can be encountered. Apart from uniform material loss, local defects such as pits and holes are common and can lead to leaks without compromising the pressure bearing capabilities of the pipe. Repairs must be designed against both main types of failure; burst stress and leakage.

Repairs made from composite materials have become a popular option to restore steel pipelines in the oil and gas production. Composite repairs can be superior over metal repairs for their corrosion resistance, fatigue performance, strength, stiffness, thermal insulation, damping and weight reduction [1]. Combined with an easier and faster deployment the use of composite repairs can lead to a reduction in costs. Probably the most common composite repair method are wrapped laminates [2], but also precured composite repairs such as hardshells [3], stand-off clamps [4] or the Clock-Spring© system [5] are available on the market. Wrapped composite repairs consist of glass or carbon fibre reinforcements and typically an epoxy matrix, although other resins are used as well.

Composite repairs perform excellent against hoop stress imposed by an internal pressure. Commonly used wrapped composite repairs were also found capable of restoring the tensile and bending properties of pipelines [6]. Not only wrapped but also composite patch repairs can achieve good results as shown by [7]. Leaks, typically caused by some types of corrosion, can be problematic. In the event of small leaking defects, the pressure forms blisters underneath the repair. The strength of the adhesion of the composite repair to the metal substrate of the pipe wall determines whether a blister starts to grow. If the adhesion is too weak, a crack will propagate in the interface between composite and metal until it reaches the edge of the repair, resulting in a new leakage. In contrast to burst failure, the surface preparation and the properties of the matrix material are of higher importance than the fibre content.

The standards ASME PCC-2/4 [8] and ISO/TS 24817 [9] provide methods for the design of composite pipe repairs against burst failure and interface debonding. The design method against burst failure has recently been under investigation [10]. Yet, the understanding of the blister forming and propagation between bi-material interfaces of ‘thick plates’ needs to be improved. The formulations of the standards, for instance, assume

* Corresponding author at: School of Mechanical & Systems Engineering, Newcastle University, Stephenson Bldg, Claremont Rd, NE1 7RU Newcastle upon Tyne, United Kingdom.

E-mail address: j.m.linden@ncl.ac.uk (J.M. Linden).

http://dx.doi.org/10.1016/j.compositesa.2015.10.026
1359-835X/

quasi-isotropic material properties for the composite repair and an infinitely stiff substrate. Additionally, the model assumes a flat disk incorporating axisymmetric or slotted through-hole defects with rectangular edges around the defect at the repair-substrate interface. Typical measures of the bi-material interface adhesion strength are the fracture toughness or energy release rate obtained by a blister test (Fig. 1). A fluid *pressurised blister test* (PBT) mimics the analytical formulation of the standards closely, but is complex in execution and measurement. *Shaft-loaded blister tests* (SLBT) are easier to control and less complex in general for the drawback of a difference in loading.

One aim of the study presented was to evaluate whether a PBT could be replaced with the less complex and partly advantageous SLBT. Mostly applied on thin films and membranes, as shown in the following review, existing analytical solutions had to be re-evaluated. A new formulation was introduced to account for the scenario of composite repairs over small leaking defects, which result in an analytical solution for the bending of thick plates. Furthermore, two types of punch heads (flat and hemispherical) were investigated. After a brief review of the SLBT, the different analytical solutions are presented. Subsequently, the methods of evaluation are outlined before the results are presented and discussed.

2. Review of shaft-loaded blister tests

An attempt to reduce the complexity of PBTs was the introduction in the form of a blister test using a mechanical force by driving a shaft with an either flat or curved punch head through a defect against a top layer, here the composite repair. SLBTs are widely conducted and provide the additional advantage over PBTs of the option to be displacement controlled. In contrast to load controlled fracture tests, displacement driven tests do not fail catastrophically (Fig. 2). Mechanical properties of the repair laminate can be determined in a clamped SLBT [11,12]. For this purpose, the repair is clamped around the edge of the defect to prevent its detachment from the substrate.

Malyshev and Salganik [14] were the first to develop an SLBT by debonding a thin plexiglass plate from a metal substrate with a punch. Several types of SLBTs can be found, but one of the most common is conducted with a hemispherically capped cylinder as punch [15–17]. Depending on the investigated material and the radius of the hemisphere, the contact zone can change throughout the loading and plastic deformations can occur. Both contact zone and plastic deformation need to be taken into account for the analytical calculation [18–20]. Flat capped punches are typically used in an 'inverted' blister test [21–23], in which the investigated film debonds from the punch. The punch is bonded to the film and pulls, while the film is clamped around the edge. Relatively little work is published that uses a flat punch pushing against a repair plate in a standard blister test [24,25]. Hemispherical heads are favoured to avoid high accumulations of stress at the sharp edges of flat capped punches, which could result in yielding and rupture of the film. Axisymmetric flat punch and plate shapes are often used, but rectangular shapes may also be found for plane strain models [26,27].

Theoretical and numerical studies were conducted on different punch and repair plate geometries, leading to different boundary conditions for the analytical solutions at the centre of the plate

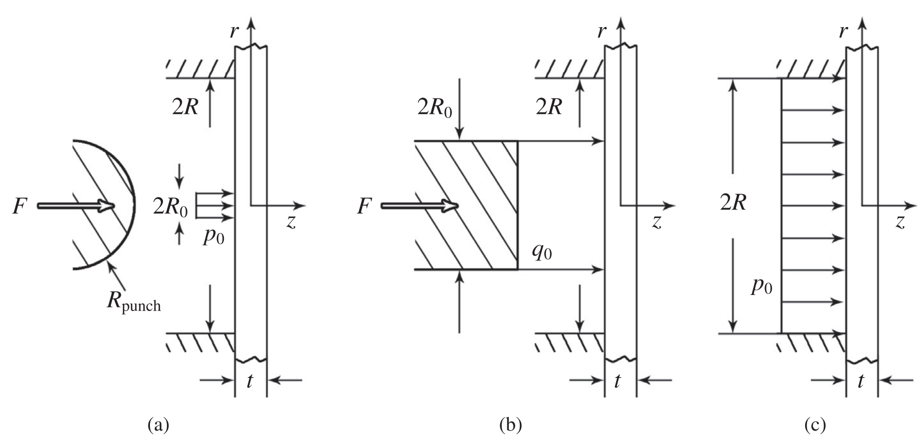

Fig. 1. Diagram of a circular disk in a blister test under load by (a) an hemispherical punch (SLBT-H), (b) a flat punch (SLBT-F) and (c) fluid pressure (PBT).

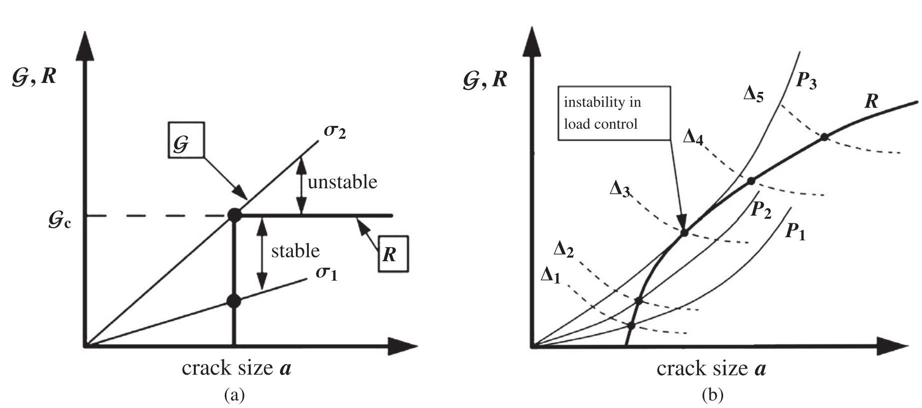

Fig. 2. Driving force against resistance R curve for: (a) linear $d\mathcal{G}/da$ with flat R curve, (b) non-linear $d\mathcal{G}/da$ and R curve showing a comparison between displacement Δ and load P driven; © of [13].