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BLISTER TEST AS AN ALTERNATIVE TO HYDROSTATIC TEST IN COMPOSITE REPAIR QUALIFICATION

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Abstract. *The qualification of composite repair systems for pipelines with through-thickness defects usually requires a number of hydrostatic tests to obtain the failure pressure. The estimation of the failure pressure is usually performed in the oil industry using linear fracture mechanics analysis in both ISO and ASME standards and both standards require the determination of a constant fracture energy, also called the energy release rate. In the case of monotonically increasing loading histories, in the framework of linear fracture mechanics, interfacial debonding occurs brutally when the fracture energy reaches a critical value. This study is an attempt to show that simpler blister tests can be used as a replacement for hydrostatic tests in the qualification of such repair systems. The idea is to obtain experimentally the critical fracture energy using blister tests. Reasonable similarity was found between the critical energy values found using shaft-loaded blister test with the ones obtained with the standard required hydrostatic tests.*

Keywords: *blister test, energy release rate, composite repair, fracture energy, hydrostatic test*

1. INTRODUCTION

Metallic pipelines are heavily used to convey a variety of fluids in the oil industry. One of the main issues faced in offshore platforms is the corrosion of such pipes and the unplanned shutdown of the transmission line. Jaske et al. (2016) describe conventional repair methods, which include the installation of steel sleeves and clamps or, in more severe damages, the complete replacement of the corroded section. Lim et al. (2016) point out that such methods have limitations like the small operational space, the need of a welding machine, which brings a risk of explosion, and the difficulty to perform the repair in joints, for instance.

Thus, researchers have developed an alternative solution to repair corroded pipelines, using composite materials. This type of repair is lighter, easier to handle and, according to Shy (1987), up to 73% cheaper in comparison with the replacement of the pipe section. However, to be used as a repair system, a composite material must first be qualified according to either ISO 24817 or ASME PCC-2 standards. Basically, these standards require several hydrostatic tests to determine the critical energy release rate for a particular composite repair system. This critical energy value is believed to be a constant. The standards assume that the curvature of the pipe wall is so small that it does not have an influence on the critical energy release rate, reducing the problem to a pressurized circular delamination between the steel substrate and the composite repair.

Moreover, this setup is also adopted in the standard blister test. Originally proposed by Dannenberg (1961), it consists in applying a coating on a rigid substrate with a center hole and using a pressurized fluid or gas to force the debonding of the coating. Later on, Malyshev and Salganik (1965) developed a simpler setup of the blister test, called shaft-loaded blister test, which uses a shaft to apply the mechanical load on the coating. This version of the blister test can be performed on a universal testing machine, therefore, the blister central deflection and the load-displacement of the shaft are easier to acquire.

2. CRITICAL ENERGY CRITERION

Both ISO 24817 and ASME PCC-2 standards, used as guidelines for qualification and design of composite repair systems, adopt a critical energy criterion for fracture. Basically, this condition is a scope of Griffith's criterion for quasi-static crack propagation, as can be seen in Eq (1), where γ is interpreted as the energy required to increase the crack area by an amount ∂A, W_d is the work done by external forces and U is the internal elastic energy.

$$\gamma=\frac{\partial(W_d-U)}{\partial A} \tag{1}$$

For structures exhibiting bulk linear elastic behavior and considering an area away from the crack tip, the difference "$W_d - U$" can be expressed in terms of the pressure p and the resulting volume V, as shown in Eq. (2)

$$W_d-U=pV-\frac{1}{2}pV=\frac{1}{2}pV \tag{2}$$

Combining Eq. (1) and Eq. (2) gives Eq. (3), from which can be seen that critical energy for fracture is a function of the applied pressure and the rate of volume variation in regards to the crack area.

$$\gamma=\frac{1}{2}p\frac{\partial V}{\partial A} \tag{3}$$

2.1. Circular defect

In order to obtain the equations for a circular type defect, used in both ASME PCC-2 and ISO 24817, a few simplifications are made. For instance, it is assumed that the pipe wall curvature is small enough to not influence the critical energy release rate and that the substrate is rigid. Therefore, the problem is reduced to what can be seen in Fig. 1, i.e., a delamination between the composite repair laminate and the substrate caused by the pressure p applied trough the circular defect.

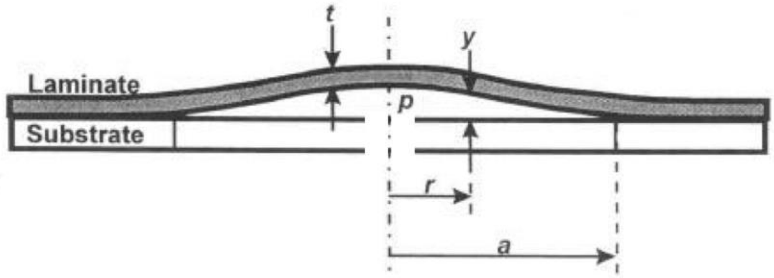

Figure 1. Delamination of repair laminate

The deflected profile is given by Eq.(4), where E_{ac} is the combined tensile modulus of the repair laminate, ν is the Poisson's ratio, and t is the laminate thickness. This is essentially the plate deflection obtained using a first order Mindlin (1951) theory of plates. For the laminate, an average shear modulus G must be experimentally determined.

$$y(r)=p\left[\frac{3(1-\nu^2)}{16E_{ac}t^3}\{a^2-r^2\}^2+\frac{3}{8Gt}\{a^2-r^2\}\right] \tag{4}$$

The work done by the external forces minus the elastic energy stored within the laminate is given by Eq. (5), where the additional term on the right derives from Sneddon's (1946) analysis of the stress distribution in the neighborhood of a crack in an elastic solid.

$$W_d-U=\pi\int_0^a py(r)rdr+\frac{4(1-\nu^2)}{3E_{ac}}p^2a^3 \tag{5}$$

Equation (6) can be found by inserting Eq.(4) in Eq. (5).

$$W_d-U=\pi p^2\left[\frac{3(1-\nu^2)}{16E_{ac}t^3}\frac{a^6}{6}+\frac{3}{8Gt}\frac{a^4}{4}+\frac{4(1-\nu^2)}{3\pi E_{ac}}a^3\right] \tag{6}$$

Moreover, since $dA = 2\pi a da$ and the defect diameter d can be written as $2a$, it can easily be shown, that the critical energy release rate is given by Eq. (7). The first term on the right hand side concerns the energy associated with Mode I fracture, while the second term relates to Mode II energy fracture.

$$\gamma=p^2\left[\frac{(1-\nu^2)}{E_{ac}}\left\{\frac{3}{512t^3}d^4+\frac{1}{\pi}d\right\}\right]+p^2\left[\frac{3}{64Gt}d^2\right] \tag{7}$$

The crack propagation will not be catastrophic as long as Eq. (8) is valid. Therefore, the critical pressure can be expressed as shown in Eq.(9).

$$\gamma < \gamma_{cr} \tag{8}$$

$$P_{cr} = \sqrt{\left\{ \frac{\gamma_{cr}}{\frac{(1-\nu^2)}{E_{ac}} \left\{ \frac{3}{512t^3} d^4 + \frac{1}{\pi} d \right\} + \frac{3}{64Gt} d^2} \right\}} \tag{9}$$

3. SHAFT-LOADED BLISTER TEST

The study by Malyshev and Salganik (1965) was the first to propose the shaft-loaded blister test as a more convenient version of the classic pressurized blister test. As Chen et. al (2014) point out, the original version of the test has a few limitations such as, the catastrophic debonding when a critical pressure is reached, and mainly, the potential rupture of the coating prior to the debonding from the substrate. Furthermore, the pressurized blister test requires an elaborated setup and pressure control system in order to track variations of pressure and blister dimensions.

To overcome these limitations, in the shaft-loaded blister test the load is applied by a spherically capped shaft to the center of the composite plate, as shown in Fig. 2.

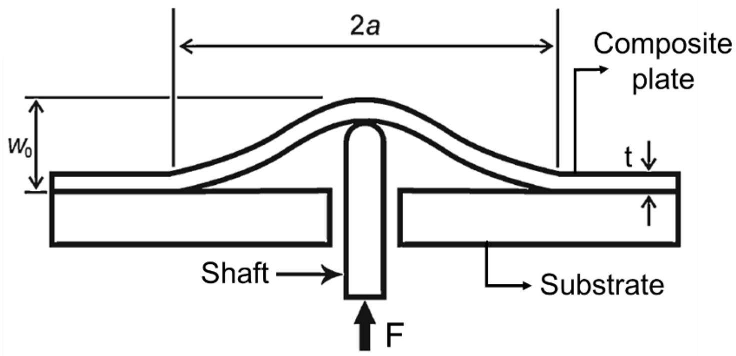

Figure 2. Schematic of the shaft-loaded blister test. Adapted from Chen et.al (2014).

As can be seen, this version presents a simpler setup and data acquisition system and can be performed on a universal testing machine. The expression for the fracture energy is given by Eq. (10). In this case, it was used a classical Kirchoff-Love theory, where *F* is the load, *v* is the Poisson's ratio, *E* is the modulus of elasticity and *t* is the repair thickness. The ensure that sudden crack growth does not occur, the criterion in Eq. (8) should be met. That is, as long as the fracture energy $\gamma_{blister}$ is lower than a critical energy $\gamma_{blister cr}$ the crack propagation is controlled and catastrophic failure will not ensue.

$$\gamma_{blister} = \frac{3(1-\nu^2)F^2}{8\pi^2 E t^3} \tag{10}$$

4. MATERIALS AND METHODS

4.1. Materials

Two composite systems were used to manufacture the test specimens. The Synhto-Glass® XT system consists of a water-activated polyurethane resin reinforced with bidirectional fiberglass cloth. The second composite system used was the Thermo-Wrap™, which employs Thermo-Poxy™ epoxy resin in conjunction with a high strength bi-directional fiberglass. Table 1 presents the mechanical properties of both systems at test temperature.

Three different size artificial through wall defects were machined in steel plates of 20 mm x 20 mm dimensions. The surfaces of the plates were prepared using an electric bristle blaster, providing a better anchor profile to the surface and removing imperfections, such as scale and corrosion. With the surface cleaned, the hand lay-up process of the composite systems was carried out.

The Thermo-Wrap system was laminated directly on the surface of the steel plate and a repair thickness of 2.64 mm was obtained. For the Syntho-Glass repair, a thin layer of adhesive was applied on the metal surface and the composite was laminated on top of it, obtaining a total thickness of 3.64 mm.

Table 1. Properties of the composite materials at test temperature.

Properties	**Syntho-Glass® XT**	**Thermo-Wrap™**
Modulus of Elasticity *E* (MPa)	6700	17400
Shear Modulus *G* (MPa)	4540	4336
Poisson's ratio *v*	0.26	0.26
Test Temperature	23°C	149°C

4.2. Methods

4.2.1. Hydrostatic test

As required by the standard ISO 24817, a minimum of nine hydrostatic tests must be performed to obtain the critical energy release rate γ_{LCL}, with a 95% lower confidence limit. Initially, Eq. (10) is used to acquire the energy release rate for each test, where p_i is the failure pressure of each specimen and $A(d_i)$ is defined by Eq. (11).

$$\gamma_i = \left(\frac{p_i}{A(d_i)}\right)^2 \tag{10}$$

$$A(d_i) = \sqrt{\left\{\frac{0{,}001}{\frac{(1-v^2)}{E_{ac}}\left\{\frac{3}{512t_i^3}d_i^4 + \frac{1}{\pi}d_i\right\} + \frac{3}{64Gt_i}d_i^2}\right\}} \tag{11}$$

Where, E_{ac} is the combined tensile modulus of the repair laminate, G is the shear modulus of the repair laminate, v is the Poisson's ratio, d_i is the diameter of defect and t_i is the thickness of the repair laminate. Equation 12 is used to calculate the lower confidence limit of the energy release rate, where t_v is the Student's value and σ is the variance of measurement of pressure, obtained by Eq. (13). The mean energy release rate γ_{mean} is given by Eq. (14).

$$\gamma_{LCL} = \left[\frac{\sum_{i=1}^{n} A(d_i)p_i}{\sum_{i=1}^{n} A(d_i)^2} - t_v\sigma\sqrt{\frac{1}{\sum_{i=1}^{n} A(d_i)^2}}\right]^2 \tag{12}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(p_i - A(d_i)\sqrt{\gamma_{mean}}\right)^2}{(n-2)}} \tag{13}$$

$$\gamma_{mean} = \left(\frac{\sum_{i=1}^{n} A(d_i)p_i}{\sum_{i=1}^{n} A(d_i)^2}\right)^2 \tag{14}$$

4.2.2. Shaft-loaded Blister Test

The shaft-loaded blister tests, as shown in Fig. 3, were performed on a Shimadzu AG-X 100kN universal testing machine. Three shafts with diameters of 10 mm, 15 mm and 25 mm were machined and connected to the crosshead. A crosshead speed of 1.25 mm/min was adopted. As mentioned in Table 1, the blister test for the Thermo-Wrap system was performed at 149 °C. Hence, in order to achieve and maintain said temperature, a thermostatic chamber was attached to the testing machine, as displayed in Fig. 4.

Figure 3. Blister test setup.

Figure 4. Blister test with thermostatic chamber.

5. RESULTS

5.1. Hydrostatic test

Figures 5 and 6 present the energy results found using hydrostatic tests for the Syntho-Glass and Thermo-Wrap composite systems, respectively. A certain amount of scattering is observed in both results, which is also seen in the blister test, as discussed in the following section.

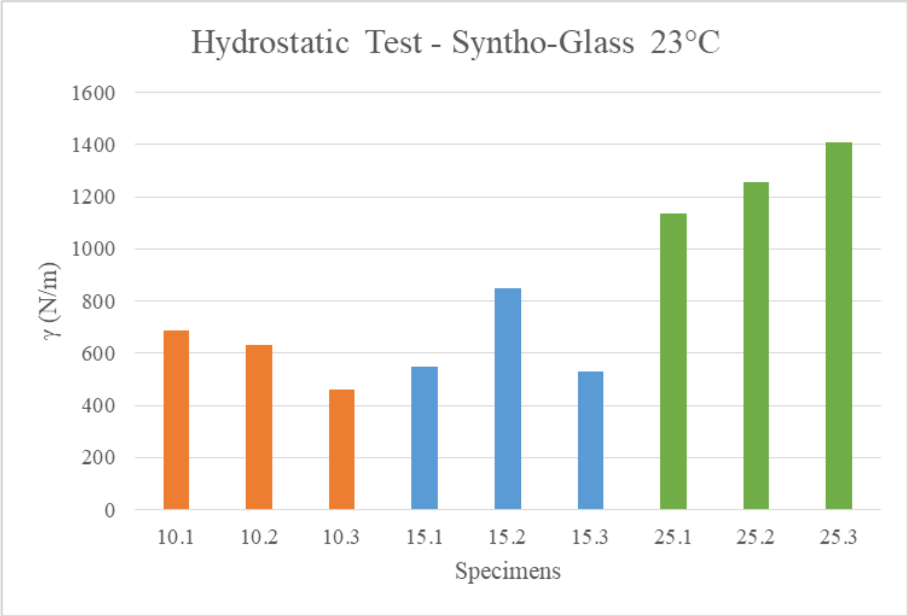

Figure 5. Hydrostatic test results for Syntho-Glass at room temperature.

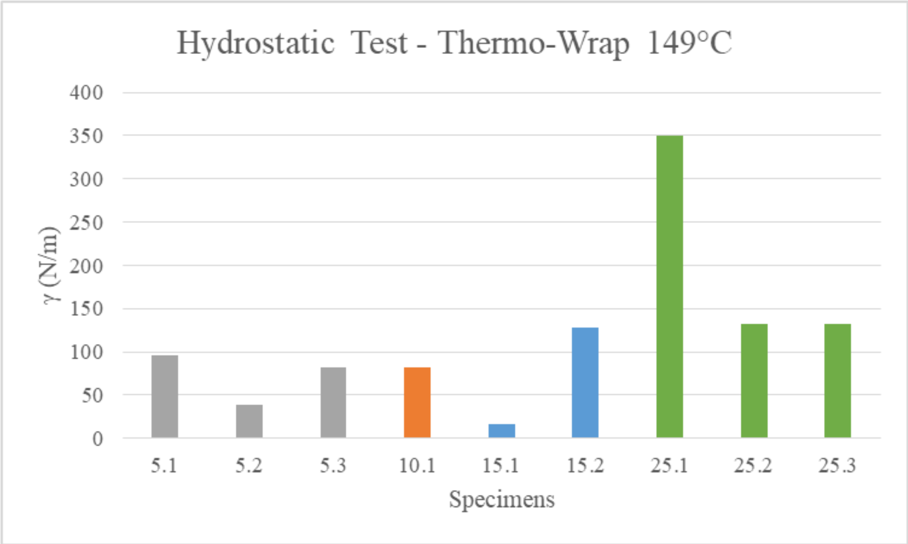

Figure 6. Hydrostatic test results for Thermo-Wrap at 149 °C.

5.2. Blister test

Figure 7 presents the critical energy values found for Syntho-Glass® at room temperature, whilst Fig. 8 shows the results for the Thermo-Wrap™ system at 149°C. The dispersion observed in both systems can be considered normal since the energy might be sensitive to many factors like surface roughness, adhesive thickness and imperfections in the lay-up manufacture process.

In the standard required hydrostatic, a similar scattering is commonly observed. Thus, to ensure the safety of the repair system, standards for composite repair qualification determine that a lower confidence limit (LCL) critical energy value must be adopted.

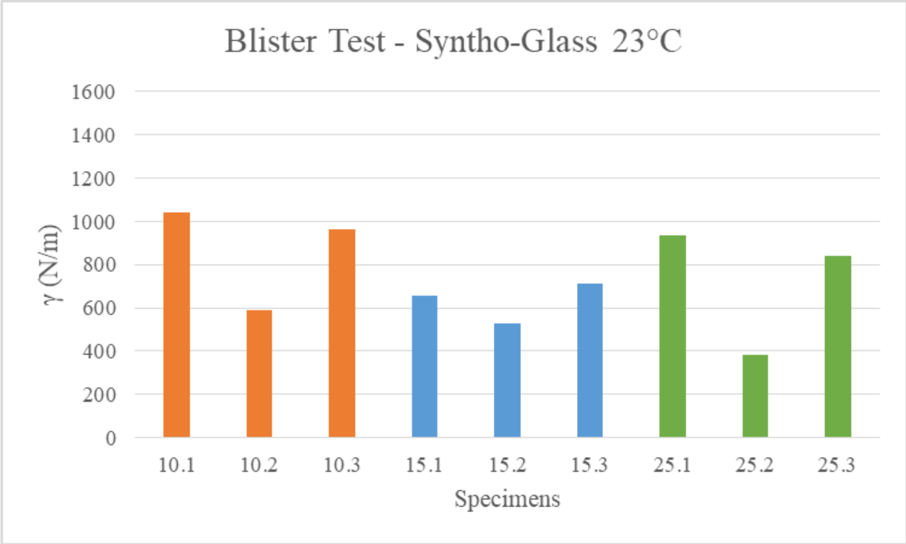

Figure 7 - Fracture energy values for Syntho-Glass system at room temperature.

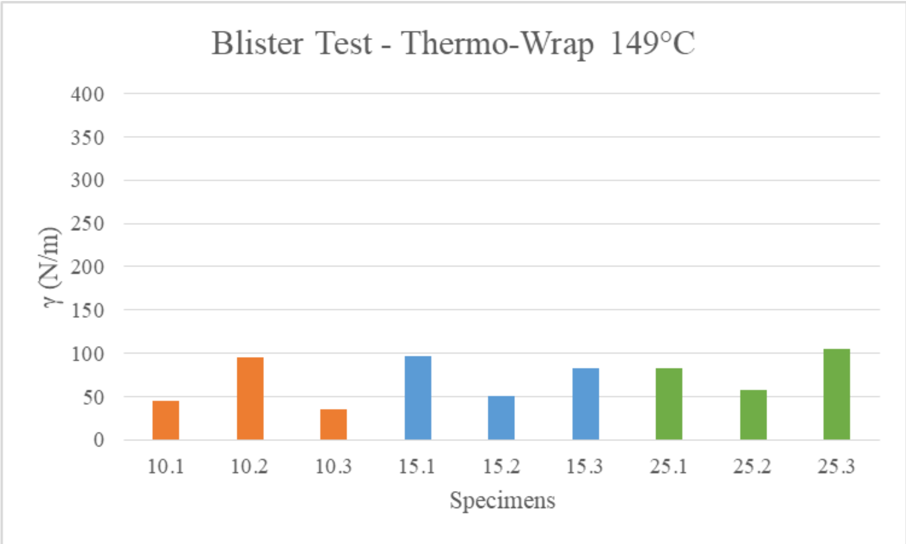

Figure 8 - Fracture energy values for Thermo-Wrap™ system at 149°C.

5.3. Comparison between blister test and hydrostatic test

Table 2 compiles the results of each repair system for both test methods. Figure 9 presents the comparison for the mean and the lower confidence limit energy values found for Syntho-Glass® at room temperature. The results obtained for Thermo-Wrap™ system at 149°C are shown in Fig. 10. As can be seen for both repair systems, blister test provided a good estimation for the critical energy release rate found in standard hydrostatic tests.

Table 2. Mean and lower confidence limit (LCL) energy values for each repair system and test method.

Test Method	Syntho-Glass® XT		Thermo-Wrap™	
	Mean Energy (N/m)	LCL Energy (N/m)	Mean Energy (N/m)	LCL Energy (N/m)
Blister Test	731.25	500.07	58.79	35.84
Hydrostatic Test	659.28	461.68	70.16	34.79

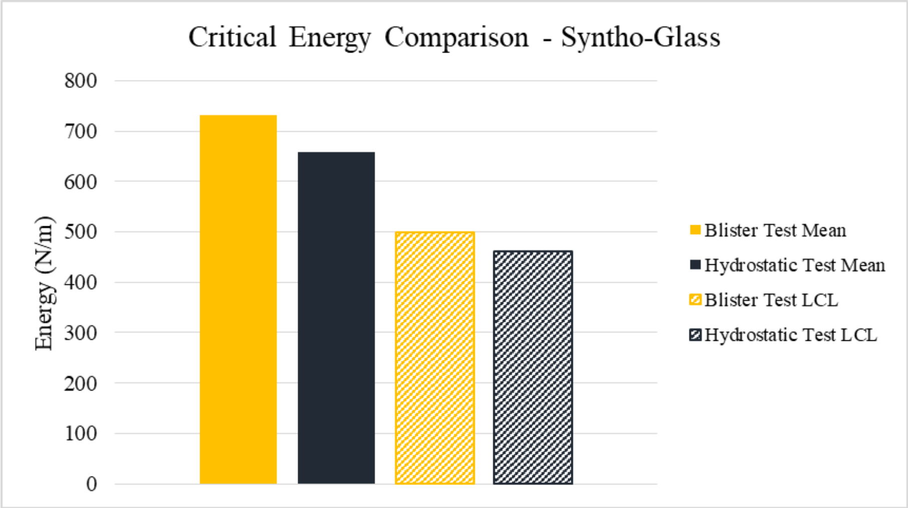

Figure 9 – Comparison of energy values found using blister test and hydrostatic test, for Syntho-Glass® at room temperature.

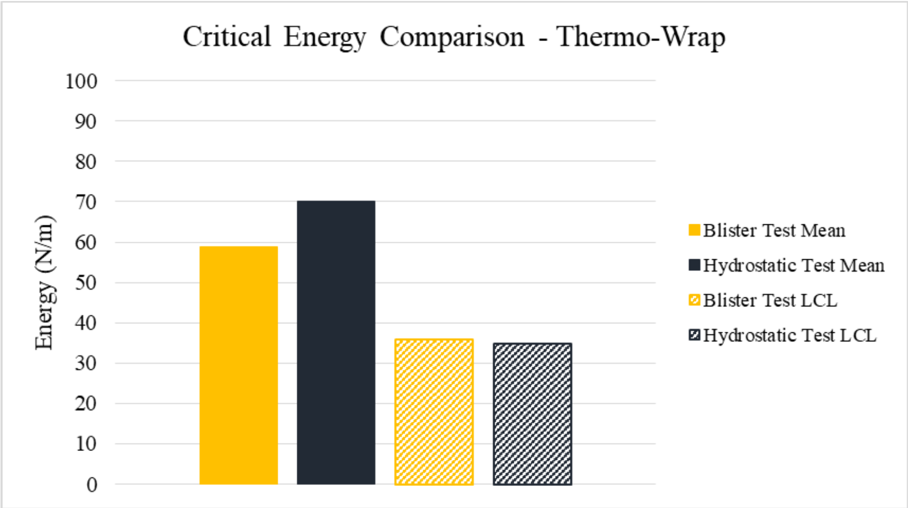

Figure 10 - Comparison of energy values found using blister test and hydrostatic test, for Thermo-Wrap™ at 149°C.

6. CONCLUSIONS

This work studied the shaft-loaded blister test as an alternative test in acquiring the critical fracture energy. It was verified that blister test estimated with reasonable approximation the critical energy found with hydrostatic tests, but more tests must be performed in order to validate the results found thus far. A next step should be to improve the analysis performed by Malyshev and Salganik (1965) including the shear contribution on the displacement. Therefore, this simpler test method presents itself as a potential alternative for hydrostatic test in the qualification of composite repairs.

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