FRACTURE MECHANICS FOR A PLATE HEAT EXCHANGER GASKET

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Abstract

A plate heat exchanger consists of a number of thin, corrugated plates with openings for two heat exchanging fluids. The plates are put together in a stack with a rubber gasket between each plate. Due to assembly pressure and high operating temperature in the plate heat exchanger, the gaskets sometimes tend to crack.

This work evaluates and implements fracture models for rubber in FE-applications. This includes performing laboratory tests to determine material characteristics for two rubber materials, supporting and also verifying FE-simulations. Experiments using pure shear test specimens are presented and the pure shear test method reflects the true condition in the gasket well.

The tearing energy criterion is thoroughly evaluated and concluded not valid for crack lengths less than 5mm. Hence, the presence of small scale cracks (material irregularities) of approximately 50μm are not supported by the tearing energy criterion or by any other fracture criterion evaluated in this work.

Stress analyses of an EPDM gasket are performed in ABAQUS, showing that the maximum principal Cauchy-stress reaches a level of 9.5MPa at a temperature of 130°C. Hence, the material strength is exceeded and fracture mechanics is ruled out as a major factor influencing rupture of gaskets.

1 Background

In a plate heat exchanger, the gasket and plate material along with the geometric shape of the gasket and the gasket groove geometry are critical factors for the performance of the plate heat exchanger. In order to improve sealing characteristics and also reduce time in the design process, Alfa Laval has started to use finite element analysis as a tool in development of new designs and for modification of existing products.

This master thesis is a continuance of a previous master thesis, *FE-analysis on a plate heat exchanger gasket* [6]. Concluding remarks in that work established that the levels of stresses not alone could make the gaskets collapse. Explanations of gasket failure are therefore sought elsewhere, investigating whether fracture mechanics is a prime factor in the solution to the problem.

2 Rubber elasticity

This chapter is founded on the thesis *Modeling of Elasticity and Damping for Filled Elastomers* written by P. -E. Austrell, [2].

Rubbers are highly non-linear materials and the simple linear elastic stress-strain relation with a constant Young's modulus E cannot be applied. It is thus necessary to describe the material behaviour using some other mathematical model, particularly the elastic property.

The constitutive relation for a *hyperelastic material* is, as well as a *linear elastic material*, defined as a relationship between total stress and total strain. The strain energy density then plays a central role in defining the constitutive relation for rubber materials. Stresses are determined by derivatives of *the strain energy density function W*, which is a function of the strain invariants

$$W = W(I_1, I_2, I_3)$$

Two common forms of the strain energy function *W*, implemented in most of the general finite element programs are the *Neo-Hooke* model, i.e.

$$W = C_{10}(I_1 - 3)$$

and the *Yeoh* model, i.e.

$$W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3$$

The elastic parameters C_{10}, C_{20}, C_{30} are the constants that describe the hyperelastic material behaviour in FE-analyses.

3 Fracture mechanics

The objective of this work was to evaluate applicable fracture mechanics approaches for rubber, and foremost for small cracks. Recent works in this field as well as traditionally used fracture mechanics methods were studied, and this chapter describes the methods that were found to be most relevant for this application.

3.1 Stress approach

Here follows a discussion of some fracture mechanic stress criteria based on *Linear Elastic Fracture Mechanics* (LEFM). Mode I and plane stress are assumed if nothing else is mentioned. The stress σ_y normal to the crack plane, versus distance r from the crack tip is plotted in Figure 1.

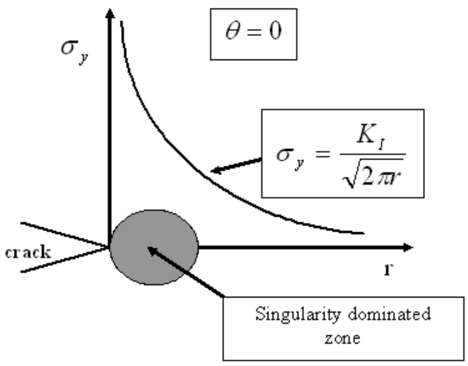

Figure 1: *Stress normal to the crack plane in Mode I.*

3.1.1 Elementary case

The elementary case approach is based on analytical solutions for simple and well-defined load cases, and the result can only be regarded as a guideline. Examples of elementary cases can be found in [7].

3.1.2 Substitution method

Given the *stress intensity factor* K_{Ic} and knowing the stresses in a point at the distance r in front of the crack tip, the substitution method can be applied. Calculate K_I; and if

$$K_I \geq K_{Ic}$$

fracture will occur. This is a traditional method confined to LEFM. In non-linear material formulations or use of hyperelastic material, (i.e. not in accordance with the assumptions defining LEFM), the substitution method is inadequate for predicting fracture.

3.1.3 Mean stress criterion

The idea of the mean stress approach [1] is to adopt the stress criterion, but instead of the stresses in a point, the mean stress acting across an area is calculated.

For an isotropic material the mean stress can be calculated as

$$\overline{\sigma}_y = \frac{1}{r_0} \int_0^{r_0} \sigma_y \, dr = \sigma_s$$

where σ_s is the strength and r_0 is a material parameter defined as

$$r_0 = \frac{2}{\pi} \frac{K_{IC}^2}{\sigma_c^2}$$

The main purpose of the mean stress approach is to use the material parameter r_0 as a criterion for the length along which the mean stress should be calculated. Fracture will occur if the mean stress exceeds the strength of the material.

3.2 Energy approach

Here follows a presentation and discussion of fracture mechanics energy approaches or non-linear approaches.

3.2.4 The tearing energy criterion

In technical rubber literature, the growth of a crack is expressed as the tearing energy T, also referred to as the fracture energy [3]. This quantity is expressed as

$$T = -\left(\frac{\partial U}{\partial A}\right)_{\ell} \qquad (1)$$

The criterion states that the crack can grow if the total elastic energy applied to the material is just sufficient to cause a small increase ∂A in the crack surface area. ℓ indicates that the partial differentiation is with respect to constant deformation.

All rubber materials have a critical or maximum value of the tearing energy T_c, which the material can withstand. The fracture criterion for crack propagation for this method is given as

$$T \geq T_c$$

The tearing energy has been found to be the most useful failure criterion for a variety of fracture phenomena in rubber, [4].

3.2.5 Cracking energy density

The article *Cracking energy density as a predictor of fatigue life under multiaxial conditions* [5], describes a new quantity (*Cracking energy density*) for predicting fracture in rubber.

The article describes fatigue calculations, but with some modifications, the method may be considered as a rapid fracture approach. Due to limited information, the method will not be a part of the computations in this work. More knowledge of the application of *cracking energy density* as a rapid fracture criterion is needed for future investigations.

For further information about this method, the reader is referred to [5].

3.3 Method evaluation

Rubber materials exhibit non-linear behaviour, hence, theories based on linear elasticity and corresponding results are fundamentally inaccurate. Furthermore, the highly stressed zone surrounding a crack tip in rubber is large compared to stiffer materials such as steel. Conclusions are thereby made that LEFM, stipulating a small singularity dominated zone in front of the crack, is inadequate for fracture analyses in rubber.

Robustness and applicability has been key factors when, in this thesis, focus have been set on the tearing energy criterion, see Section 3.2.4. The simplicity of managing laboratory tests parallel to corresponding finite element analyses makes the tearing energy criterion the best way to address the problem stated in this work.

A method that purely supports small cracks, like irregularities in the rubber, was not found when evaluating different fracture approaches. This may cause problems when the tearing energy criterion is applied to small initiated cracks and in particular to the gasket geometry, where micro-cracks are supposed to be present in the model.

4 Experimental

The objective of testing was to evaluate parameters for a material model giving a well-defined base for computer-aided simulations in the FE-software ABAQUS. Furthermore, calculation of critical tearing energies in tests will support fracture analyses performed in Chapter 5.

The elastic parameters of the material model, and the critical tearing energy, T_c, for two different rubber materials, NBR and EPDM were determined. In testing, a pure shear test specimen was used, a common and well suited test piece for determination of rubber characteristics.

4.1 Definition of pure shear

The pure shear specimen is usually made from a thin rectangular strip of rubber; connected to rectangular strips of metal, see Figure 2. The state of stress appearing in the test piece during loading is similar to the stress state in the zone where cracks are likely to occur in the compressed gasket.

Figure 2: *The pure shear specimen.*

The tearing energy for the pure shear tests can easily be determined by an approximation of Equation (1), giving

$$T = Wh \tag{2}$$

where W is the strain energy density and h is the height of the pure shear specimen.

4.2 Test procedure

A hydraulically driven MTS (Material Test System) machine was used for testing the rubber specimens.

Two different tests were performed, tests with no initiated crack and tests with initial crack lengths of 3mm or 30mm. A total number of 20 pure shear specimens were used during testing. The pure shear tests without cracks were performed to determine the material parameters for NBR and EPDM, i.e. the *Yeoh* or *Neo-Hooke* constants discussed in Chapter 2, furthermore, to determine the strength of the rubbers. Data from tests with initiated cracks provided information for evaluating fracture mechanic properties.

One NBR specimen was loaded with a cyclic deformation, see Figure 3.

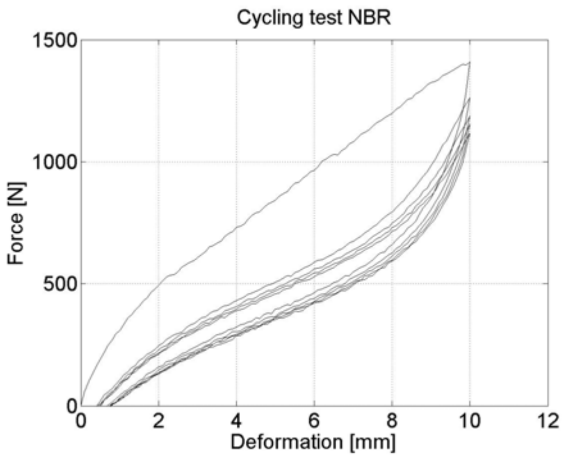

Figure 3: *Pure shear cycling test for NBR.*

The cycling test clearly indicated the *Mullin's effect* [2]. Assembling the plates in the plate heat exchanger in only one step, and thereby loading the rubber gaskets in the plate heat exchanger according to the first loading sequence, the gasket will not be influenced by Mullin's effect. The elastic parameters were fitted to first cycle behaviour using the *least square method* [2].

4.3 Results

The strength of NBR and EPDM calculated from tests are summarized in Table 1. The Cauchy-strength is the true strength, i.e. accounting for the area reduction.

Table 1: *The strength of NBR and EPDM.*

Rubber	Nominal	Cauchy
NBR	5.8MPa	13.4MPa
EPDM	4.5MPa	7.6MPa

Considering the stiffness of the tests appearing more as linear elastic at higher stretches, the *Neo-Hooke* material model better represents the true stress-stretch relation than the *Yeoh* model and therefore is used as material description in the finite element analyses.

The critical tearing energies T_c for NBR and EPDM were calculated from crack tests according to Equation (2), generating the results shown below

- NBR: T_c=8.6N/mm
- EPDM: T_c=12.2N/mm

4.4 Discussion

The strength of the rubbers determined to ~5MPa was not expected since in a previous master thesis [6], a nominal strength of 22MPa for NBR was proposed. The strength of 22MPa was given for a tensile test, but as discussed earlier in this work, a pure shear test reflects the true load case better and also decreases the strength considerably. Given the major reduction of strength and the modified material properties, a new objective of this thesis is founded; new stress analyses of the gasket component must be computed and evaluated, comparing stress levels with material strength. After all, fracture mechanics might not be the answer to the rupture of gaskets at Alfa Laval.

5 FE-analysis of crack propagation

Material characteristics were determined according to tests presented in Chapter 4, constituting the input for FE-analyses. To evaluate the suitability of fracture criteria chosen in Section 3.3, simulations were made implementing criteria in procedures applied on a pure shear geometry with different crack lengths. All FE-simulations were carried out using the FE-software ABAQUS/Standard and this chapter describes the fracture simulations and presents the results. For further information concerning fundamental theory of FEM and simulations in ABAQUS/Standard, the reader is referred to [6].

5.1 Model

The pure shear body is modelled in ABAQUS/CAE with material data and boundary conditions representing the case of the pure shear body used in experiments. The 2-D model including the boundary conditions is seen in Figure 4. The initiated crack is simulated by leaving an unrestricted boundary in the symmetry plane (lower left corner of Figure 4), see Figure 5.

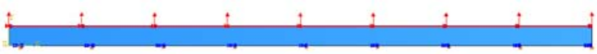

Figure 4: *Pure shear model.*

By translating the upper boundary away from, and normal to the crack plane, the crack opens, see Figure 6. The crack tip is seen to exhibit a stress concentration that will generate crack propagation when a fracture criterion is met.

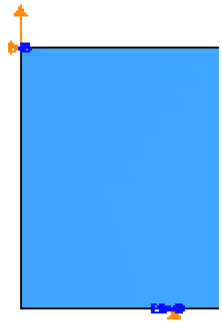

Figure 5: *The unrestricted boundary in the symmetry plane.*

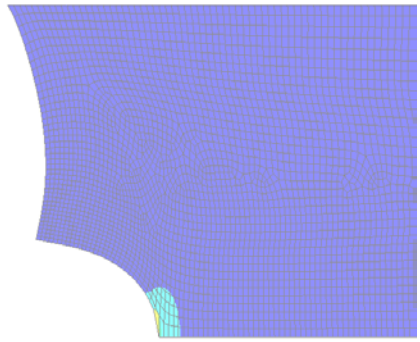

Figure 6: *Crack opening during deformation of a 3mm initial crack.*

5.2 Computational procedure

As discussed in Section 3.3, the tearing energy criterion was implemented and evaluated through FE-analyses for the pure shear specimen. The fracture analyses were performed in a step procedure as follows:

- Run an analysis with a specific deformation and crack length a, and record the stored elastic strain energy U in the body.
- Increase the crack length with an increment da.
- Run a new analysis with the same boundary deformation but with the crack length $a+da$, and record the stored elastic strain energy in the body.
- Calculate the difference in elastic strain energy between the two analyses, and calculate the tearing energy T.
- If $T>T_c$, fracture will occur.

Analyses were performed for eight different crack lengths from 50µm to 30mm for both NBR and EPDM, where crack lengths less than 100µm represent micro cracks. Performing FE-analyses of micro cracks in the plate heat exchanger gasket requires verification of the validity of small crack analyses for pure shear specimens.

5.3 Results and discussion

In this paper and in this section only the results from analyses with EPDM are presented.

Analyses were carried out generating tearing energies during deformation sequence for six different initial large scale crack lengths, see Figure 7. The experimentally determined critical tearing energy is introduced in the figure defining when crack propagation would start according to a fix strain energy release rate, i.e. constant T_c over all crack lengths.

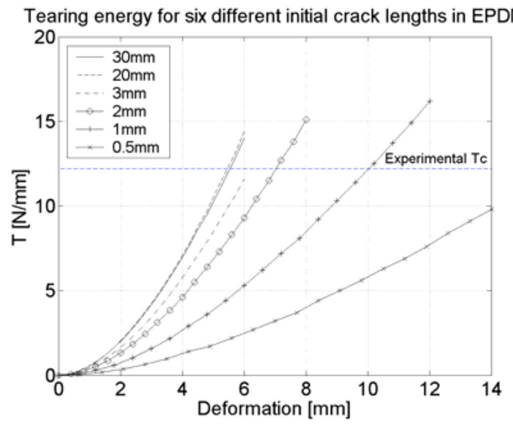

Figure 7: *Tearing energy for six different large scale initial cracks in EPDM.*

The rubber material consists of micro cracks with a size of approximately 50μm and according to tests in Chapter 4 the specimens without initiated crack sustained a deformation of 7mm for EPDM. Small crack analyses, see Figure 8, show that T for EPDM reach 0.4 N/mm for a crack of 50μm at critical deformation (70% strain), but at this deformation T should be equal to T_c if the tearing energy criterion is a valid approach for small crack analyses in this rubber.

According to the theory of a material parameter T_c constant over all crack lengths, small initial crack lengths would asymptotically reach infinite deformation meeting the critical tearing energy, see Figure 8. Hence, this criterion has a limit of valid application requiring the crack length to be large scale.

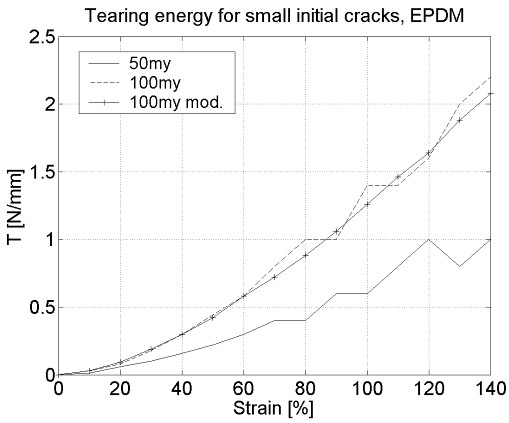

Figure 8: *Tearing energy for small initial crack lengths.*

Figure 9 gives guidance of validity showing adequate representation for crack lengths exceeding approximately 5mm. A fracture mechanics approach that purely supports small cracks with an approximately size of 50μm to 100μm was not found, which caused problems when material irregularities were supposed to be simulated in ABAQUS/Standard.

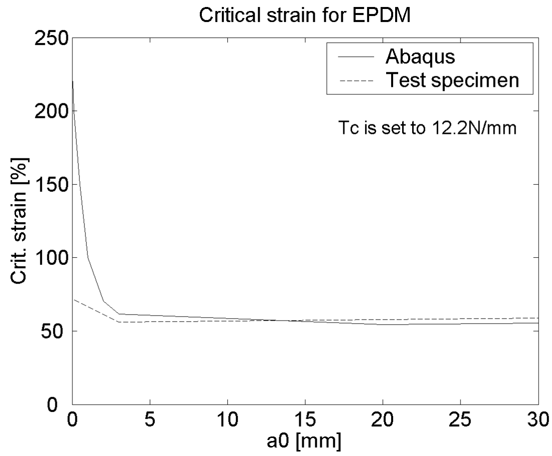

Figure 9: *Guidance of validity for the tearing energy criterion.*

6 Stress analysis on a plate heat exchanger gasket

Using parameters from a multi cycled material behaviour, it was concluded in [6] that the maximum principal stresses in a similar gasket reached a level of 7MPa. It was also assumed that the nominal material strength of the NBR rubber was 22MPa.

First of all, as discussed in Chapter 4 the material strength of the gasket is better represented by using a pure shear test than using the special case of a tensile test. According to the test results reported in Chapter 4, the pure shear nominal strength for NBR and EPDM were determined to 5.8MPa and 4.5MPa respectively.

Secondly, assembling the plates in the heat exchanger in only one step, and thereby loading the rubber gaskets according to a first loading sequence, the material parameters were set accordingly.

Considering the modifications discussed above, new FE-analyses of the plate heat exchanger gasket were performed. With the new, radically decreased material strength, it was possible that the stresses in the gasket reached and exceeded the material strength.

The analyses were carried out using ABAQUS/Standard and ABAQUS/Explicit, but in this paper only the ABAQUS/Standard results are presented.

6.1 FE-model

The load simulations of the gasket consist of an assembling step when the plates come in contact and compress the gasket in between. Then, a following step simulates the temperature rise in the gasket when the two heat exchanging fluids stream through the plate heat exchanger.

The geometry was provided by Alfa Laval, see Figure 10, and is a cut out part of the plate heat exchanger consisting of a piece of a rubber gasket placed between two corrugated plates.

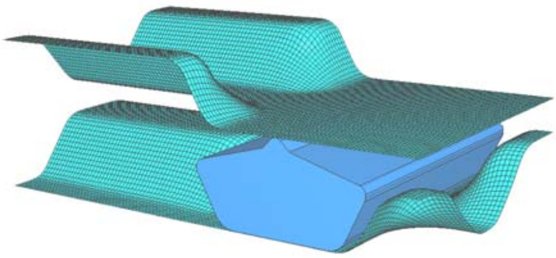

Figure 10: *The model, consisting of a cut out part of the plate heat exchanger.*

The cut out geometry represents the exterior edge of the plate heat exchanger and the plates are supported by gaskets on both sides. Considering this plate stack symmetry and the relatively stiff stainless plates, the deformation of the plates is negligible, and therefore set as rigid in FE-analyses.

Gaskets made of EPDM rubber tend to crack more frequently than NBR gaskets; hence the rubber type used in these FE-simulations was EPDM, described with the *Neo-Hooke* parameter.

Lowering the upper plate 2.3mm towards the bottom plate until contact occurred between the plates simulated the compression when the plate heat exchanger is assembled.

The gasket is glued to the bottom plate, thus the bottom of the gasket was set encastered. The gasket was also prescribed with symmetry and therefore only half of the gasket part was modelled.

The operating temperature of the plate heat exchanger is in reality approximately 130°C and considering a room temperature of 20°C, a temperature load of 110°C was applied uniformly to the model.

6.2 Results

A schematic assembly of the rubber gasket compressed between the rigid plates after loading are seen in Figure 11.

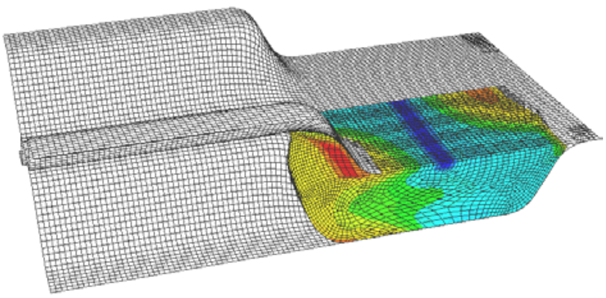

Figure 11: *Overview of the assembled components at 130°C.*

Figure 12 shows maximum principal stresses in the gasket after complete loading, i.e. after compression and applied temperature. Figure 12 gives that the maximum principal stress reach 9.5MPa after the temperature load was applied.

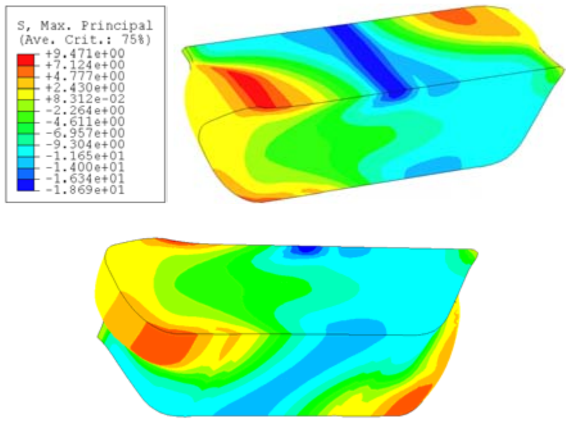

Figure 12: *The maximum principal stresses, MPa, in the gasket after complete loading.*

Figure 13 shows the critical part of the gasket exceeding the EPDM strength of 7.6MPa. To the right in this figure the highly stressed zones exceeding 6MPa are presented as possible problem areas.

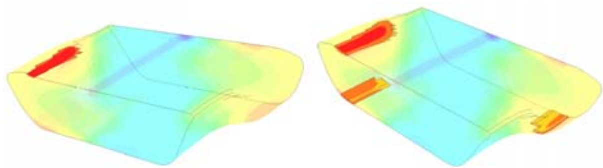

Figure 13: *Left: elements exceeding the strength of 7.6MPa. Right: highly stressed elements exceeding 6MPa.*

6.3 Discussion

The cause of rupture in the gaskets is explained by the high levels of principal stresses, which are exceeding the strength during the temperature load. As concluded before these analyses, fracture mechanics might not be the answer to the failure of gaskets at Alfa Laval.
Looking at Figure 13, it is clear that the maximum principal stresses exceed the critical strength of the EPDM rubber. The zones where high principal stresses occur also correspond very well to the flaws and damages seen in heat exchangers gaskets at Alfa Laval.

The internal pressure of the streaming fluids acting on the inside part of the gasket is not simulated in analyses due to simulation complexity. The internal pressure would probably lower the stresses marginally by holding back the extrusion of the gasket. However, this would not affect results gravely.

The analyses conclude that fracture mechanics is ruled out as a prime factor in the failure of gaskets. Instead, well identified material strength at first cycle loading constitute the solution of the problem, which can be solved using simple stress analyses.

The strength of the rubber can be determined with different test methods such as equibiaxial deformation, shear deformation and biaxial deformation. The strength differs considerably depending on these deformation modes. The different tests leave different paths in the (I_1,I_2) diagram, see Figure 14. Introduce the critical strain invariants, which can be obtained from the different test methods discussed above, as a fracture criterion in the (I_1,I_2) diagram in Figure 14. This criterion can be evaluated for different temperatures and the criterion might be appropriate as a failure criterion for stresses or strains in rubber. Investigation of this criterion is an interesting subject of future work.

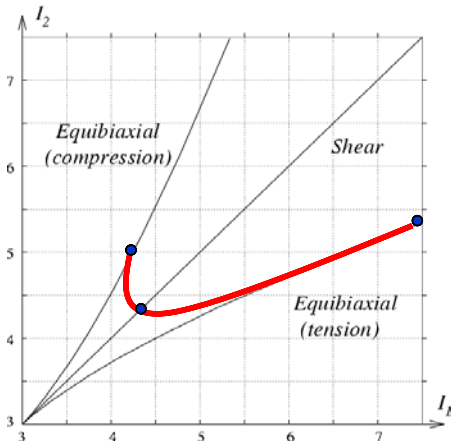

Figure 14: *The fracture criterion introduced in the (I_1,I_2) diagram.*

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