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Interactive comment on "What happens to Fracture Energy in Brittle Fracture? Revisiting the Griffith Assumption" *by* Timothy R. H. Davies et al.

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Interactive comment on "What happens to Fracture Energy in Brittle Fracture? Revisiting the Griffith Assumption" by Timothy R. H. Davies et al. Timothy Davis (Referee) davis@gfz-potsdam.de Received and published: 24 June 2019 Response We are grateful to Davis for his detailed comments, to which we respond as follows: General comments Comment "Some broad statements are made suggesting Griffith theory (1921) may be invalid".

Response: We wish to emphasise strongly that this is not a correct summary of our manuscript. In section 2 we have written "Whether or not this assumption is true has no effect on the validity of the Griffith fracture theory, which only addresses the mathematical requirements for a crack to enlarge – i.e. the value of FSE. The theory is not about SFE and says nothing about the complex chemical processes associated with exposure of fresh material by enlargement of cracks." This makes it clear that we are questioning only the Griffith (1921) assumption about the fate of elastic strain energy once the crack has been extended, not the theory itself.

Changes in manuscript: None

Comment: "the authors outline the theory with equations clearly in the introduction chapter to show it is understood";

Response: because we are not questioning anything within the theory itself such an outline would not be relevant to our arguments.

Changes in manuscript: None

Comment: "provide an explanation later in the manuscript some reasons as to why this long-standing assumption has previously prevailed for so long."

Response: We shall certainly do this; as we already state in section 3.1, "Analysis of sub-micron fragments has only recently become possible, so that the large proportion of total surface area associated with this fraction can now be identified and quantified. . .", and we shall develop this into a paragraph explaining that only when sub-micron fragments can be measured does the full surface area created by fragmentation become apparent and the energy budget deficit become evident. This is demonstrated by the fact that in debris from a rock avalanche analysed by Davies et al (in press), over 90% of the surface area is associated with fragments less than 1 micron in diameter – this is already stated on p 18 line 9.

Changes in manuscript: Penultimate paragraph of section 6: That such a fundamental assumption about the fate of fracture energy could remain unchallenged for so long (almost a century) appears peculiar at first sight. However, as mentioned earlier, the numerical difference to energy budgets resulting from the assumption only becomes significant when considering phenomena in which large numbers of sub-micron grains are formed, and when technologies are available to allow the finest fractions to be quantified. In earth sciences the relevant phenomena are rock avalanches, earthquakes and bolide impacts, whose sedimentologies have only recently been investigated, while laser size analysis and electron microscope apparatus are also relatively recent arrivals on the particle-size distribution scene. Specific Comments Comment: "The abstract attempts to describe the paper but is more leading than clearly describing the setup and results that test the quoted long-standing assumptions concisely. It also conclusively suggests that most of the energy is radiated from the tip as elastic wave energy but no data in the article is provided to validate this statement, this is only postulated later in the discussion section. I suggest the abstract is rewritten such that both the experiments/results are summarised, not just the interpretation of the results." Response: We shall be very happy to follow this useful and constructive suggestion.

Changes in manuscript: Abstract. Laboratory experiments involving unconfined compressive failure of borosilicate glass cylinders quantified the size distribution of the resulting fragments and the elastic strain energy released at failure. The data were carefully assessed for potential inaccuracies in surface area calculation, of the contribution of energy from the compression machine relaxation during specimen failure, and of possible variations in the specific fracture energy of the specimens. The data showed that more new surface area was created during the failures than would be possible if the long-standing assumption, that all the energy involved in creating new rock surface area in brittle material is taken up by the newly-created surfaces as surface potential energy and is not available to do further work, were valid. We therefore conclude that the assumption is not valid. This conclusion is supported by independent data from a previous investigation whose authors did not pursue this particular application. Our result does not affect the validity of Griffith fracture mechanics, and is significant only when large numbers of very fine fragments are created by brittle fracture, as in rock-avalanche motion and earthquake rupture, and are identified in particle-size distributions. In such situations our result is very significant to understanding of fracture energetics.

Comment: “In chapter Machine strain energy and specimen strain energy I am unsure to whether there is enough detail on the mechanical system. In chapter 9.2.1 Pollard and Fletcher, Fundamentals of structural geology (2005) machines can be categorised as a ‘stiff or ‘soft’ testing machines, relative to the sample. This definition includes the energy stored in machines frame and does not only concentrate on the material properties of parts of the machine in contact with the sample and as such, is an important detail. Some evidence that the post failure behaviour of this setup is stable is desired. Without such discussion how can readers be certain about the energies in the system that are discussed?”

Response: The testing machine is commercially marketed as having a stiff frame. The only relevance of the post-failure behaviour of the setup is the energy that can enter the fracturing body during its failure due to rebound of the machine frame during this failure. This very topic is discussed in sufficient detail in section 3.3 of the manuscript to demonstrate that the contribution of machine energy to the failure process of the specimen is small – and certainly not large enough to affect the energy budget to such an extent that our questioning of the Griffith assumption is called into question. Changes in manuscript: None

Comment: “How confident are the authors on stating a single value for the empirically derived free surface energy criteria of Pyrex described in Wiederhorn (1969)/Lange (1971). For example, Table 2 of Wiederhorn gives a standard deviation of $\pm$5% for borosilicate glass fracture surface energy and Lange also gives a $\pm$5% scatter. Some remarks on potential variations in the literatures empirical value of this properly with some estimated standard deviation or maximal/minimal values would be more suitable and figure 8 should be updated to show this. Following on from this, is there evidence the glasses used in the experiment have the same values as those in the literature? Note the detailed annealing setup to create identical thermal history of the glass slides used in Wiederhorn (1969) is different. It would help to add some discussion of how well the material properties of the glasses used match/deviate from those detailed the literature."

Response: We note firstly that altering the value of specific fracture energy of borosilicate glass has negligible effect on our data and conclusions. We have amended Fig. 8 to show a $\pm$ 5% variation in fracture energy, and it makes no difference at all to the significance of the plot.

Commercial and scientific data are unanimous in stating that the fracture energy of borosilicate glass is close to 4.5 Jm-2, and Kolzenberg et al (2013) also adopted this value; we emphasise again the fact that our data are similar to those of Kolzenberg et al (2013), so it is most unlikely that our specimens were in any way unrepresentative of borosilicate glasses.

Changes in manuscript: We have amended the dashed line in Fig. 8 to represent a possible $\pm$5% variation in fracture energy of Pyrex, from 4.28 Jm-2 to 4.72 Jm-2, and amended the figure caption correspondingly. We have also altered the final column of Table 3 to show the maximum possible surface area under the Griffith assumption with the lowest possible value of U = 4.28 Jm-3.

Comment: "It is of interest to discuss if the findings of this study only work for solids in compression. If not, discuss why previously estimated surface energies of previous studies such as Wiederhorn (1969) and Lange (1971) match so well?"

Response: While the stresses applied to the specimens were compressive, the resultant stress fields within the specimen leading to and at failure would not have been purely compressive. It is well-known, for example, that diagonal shear stress concentrations occur in cylinders under axial compression. What is important to our experiments is the quantity of elastic strain energy stored in the specimen at failure; because different applied stress geometries generate different internal stress fields they will also result in different stored energies and thus different fragment size distributions.

Nevertheless, even if our chosen setup is particularly suited to creating large numbers of small fragments, this does not alter the conclusion that the Griffith assumption was violated in our case. This is sufficient evidence that the assumption – which was inferred by Griffith (1921) to apply universally, and has since been held to apply universally – is false.

Changes in manuscript: None

Comment: “Chapter 10.7 & 10.8: Jaeger, J.C., Cook, N.G. and Zimmerman, R., 2009. Fundamentals of rock mechanics. John Wiley & Sons. Here it is stated: “Irwin (1958) extended Griffith’s concept by pointing out that in many materials, as a crack grows, energy must also be expended to create a damaged zone of irreversible plastic deformation ahead of the crack tip. In rock, this zone may consist of crushed grains, micro-cracking, etc.” Do the authors believe there is a way to differentiate such micro cracking in their particle diameter distributions (Fig 3) and would this account for the additional fracture surface they see? It must also be noted that the experiments of Wiederhorn and Lange calculate the fracture surface energy based on the propagation length of a pre-existing crack at the scale of the sample macroscale sample (75 by 25mm/ 300 by 150 mm). No focus in these studies is given to estimating micro cracking (if there was any) close to the crack plane/tip, as such are these empirical values valid for the scales used in this study?”

Response: The Irwin (1958) extension assumes irreversible plastic deformation. In cracking of Pyrex glass if there were crushed-but-not-disaggregated grains, or microfractures in the surviving fragments, they represent additional fracture surface area created that would not be accounted for in our calculation of apparent surface area from the particle-size distributions. That is, if there is micro-cracking distributed across any surfaces, we would not see it as additional surface area. Hence, if much microcracking were present, it would only make the problem much worse – that is, the true energy budget would be even more in deficit. But if our Fig 4 is representative of the fragments, micro-cracking is not a major feature (although it is present).

Davis raises the question of scale dependence of borosilicate properties, but fracture surface energy is not supposed to be a scale-dependent property for any material.

Changes in manuscript: None

Comment: “Reference 3 (Hungr): No reference to free surface energy or the energy sink in this publication, it deals with. Frictional experiments.

Response: The reference Hungr and Morgenstern, 1984 is not cited and will be deleted. However the reference Hungr, 2006 does refer to rock fragmentation as an energy sink.

Changes in manuscript: Delete reference Hungr and Morgenstern (1984)

Comment: “Reference 5 (Livne): I am not sure this this is appropriate for the point being made, firstly they are not using free surface energy in the publication, instead this focusses on testing how well linear elasticity applies and how plasticity (or at least non-linear elastic deformation) at the tip is an energy sink. Correct me if I am wrong but from what I understand basic Griffith failure theory is not directly being used here.”

Response: Davis is correct. However, as stated above, it is not basic Griffith theory that is the topic of our manuscript, it is the fate of energy involved in extending a crack in brittle material once the new crack has been created. The relevance of Livne et al. (2010) in the present context is simply that it adopts the Griffith assumption that the energy is dissipated at the crack tip as the crack extends.

Changes in manuscript: None

Comment: “Technical corrections In introduction page 2 line 16: change ‘gravity’ to ‘gravitational’. In introduction page 3 line 10 change ‘to understanding’ to ‘to the understanding’.

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