Accepted Manuscript

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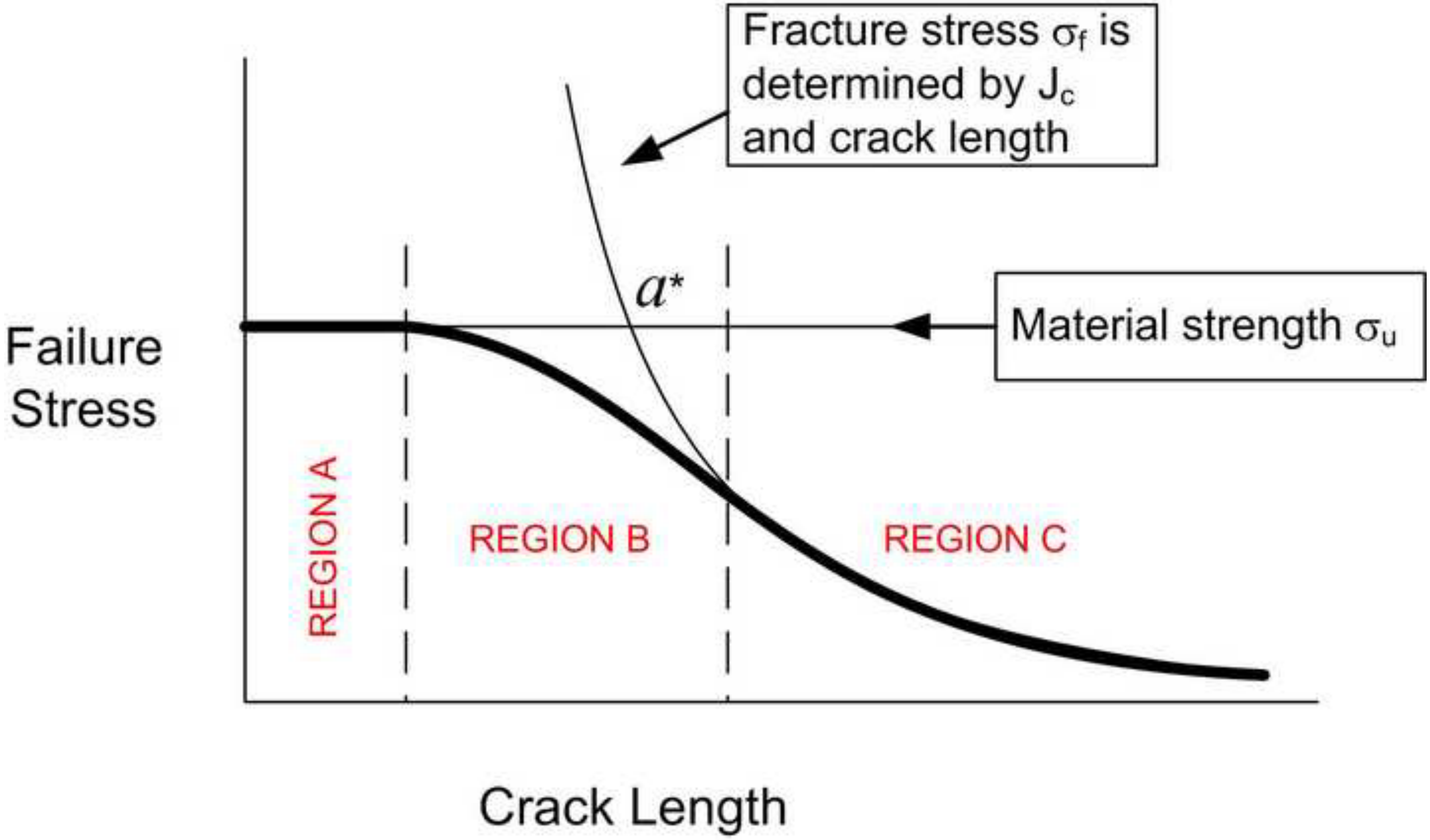
PII: S1751-6161(11)00289-X
DOI: 10.1016/j.jmbbm.2011.09.018
Reference: JMBBM 477

To appear in: *Journal of the Mechanical Behavior of Biomedical Materials*

Received date: 6 July 2011
Revised date: 29 September 2011
Accepted date: 30 September 2011

Please cite this article as: Taylor, D., O'Mara, N., Ryan, E., Takaza, M., Simms, C., The fracture toughness of soft tissues. *Journal of the Mechanical Behavior of Biomedical Materials* (2011), doi:10.1016/j.jmbbm.2011.09.018

Graphical Abstract



Highlights

- New data from fracture experiments on muscle tissue,
- A wide range of specimen sizes as well as crack lengths.
- Reanalysis of all published data on fracture toughness of soft tissues.
- We conclude that most of this data is not in fact measuring toughness at all.
- Toughness of most soft tissues is so high that cracks will not normally propagate.

The Fracture Toughness of Soft Tissues

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Abstract

Fracture toughness is important for any material, but to date there have been few investigations of this mechanical property in soft mammalian tissues. This paper presents new data on porcine muscle tissue and a detailed analysis of all previous work. The conclusion is that, in most cases, fracture toughness has not in fact been measured for these tissues. Reanalysis of the previous work shows that failure of the test specimens generally occurred at the material's ultimate strength, implying that no information about toughness can be obtained from the results. This finding applied to work on cartilage, artificial neocartilage, muscle and the TMJ disc. Our own data, which was also found to be invalid, gave measured fracture toughness values which were highly variable and showed a strong dependence on the crack growth increment. The net-section failure stress and failure energy were relatively constant in large specimens, independent of crack length, whilst for smaller specimens they showed a strong size effect. These findings are explained by the fact that the process zone size, estimated here using the critical distance parameter L, was similar to, or larger than, critical specimen dimensions (crack length and specimen width). Whilst this analysis casts doubt on much of the published literature, a useful finding is that soft tissues are highly tolerant of defects, able to withstand the presence of cracks several millimetres in length without significant loss of strength.

Keywords: Fracture Toughness; Strength; Soft Tissue; Cartilage; Muscle

Introduction

Fracture toughness is a mechanical property which measures the ability of a material to resist the propagation of cracks. A typical test for fracture toughness involves propagating a crack through a sample of material and measuring the energy required to create a given amount of new crack area, denoted J_c. The importance of this property is that it describes the "defect tolerance" of the material: its ability to tolerate the presence of cracks and other defects without significant loss of strength.

Fracture toughness has been measured for a wide variety of engineering materials and there have been many studies of this property in the body's hard tissues: bone and teeth. To date, however, there have been relatively few attempts to measure fracture toughness for mammalian soft tissues, despite the fact that cartilage, muscle, skin etc are known to suffer from cracks and other kinds of mechanical damage (e.g. (Woodhouse and McNally, 2011)) which may result in pain and impaired function. These tissues must have sufficient toughness to resist the propagation of *in vivo* defects such as cuts and internal lesions, over the time period in which healing processes can operate. In addition, all materials contain microscopic defects which were created when the material was first made. The strength of a material may be limited by its tolerance of these inherent defects.

The interaction between the two material properties of strength and toughness can be visualised on a plot of failure stress as a function of crack length, as shown in fig.1. For a sample of material containing a relatively long crack, failure will occur as a result of crack propagation, at a stress which is a function of the crack length. For the particular case of a linear, elastic, isotropic material the relationship between failure stress σ_f and crack length a is:

$$\sigma_f = \frac{1}{F}\sqrt{\frac{J_c E}{\pi a}} \qquad (1)$$

Here E is the Young's modulus of the material and F is a constant which depends on the geometry of the crack and of the sample, and on the type of loading. The parameter $(J_cE)^{1/2}$ is often rewritten as K_c, the critical stress intensity factor. For anisotropic materials, i.e. those in which E varies with direction, the energy term J_c can still be measured experimentally but the relationship between it and K_c is different. For materials which show non-linear elasticity and/or plasticity, J_c can still be defined but K_c cannot: no single equation exists to describe the failure stress for these more complex materials but the dependence as shown on fig.1 is of the same general form: the stress increases with decreasing crack length, becoming asymptotic as the crack length approaches zero.

A second line can be drawn on this plot, representing the ultimate strength of the material, σ_u, defined as the stress at which it fails when the crack length is zero, i.e. when the test is conducted on a plain sample of material. This will be a horizontal line on the figure and so will necessarily intersect with the other line at some crack length a*. The implication is that the material will be completely tolerant of all cracks smaller than this length, since the failure stress cannot rise above σ_u. In practice, however, the behaviour is rather more complicated than this. Fig.1 shows a third line representing typical experimental results. As crack length decreases, the actual failure stress deviates from the ideal value predicted based on the fracture toughness. For very small crack lengths the failure stress does indeed become equal to the material strength, but there is a significant intermediate region in which it is less than would be predicted by either a strength-based model or a toughness-based model. In summary we can define three regions:

Region A: cracks so small that they have no effect on the failure stress. Tests will measure the material's strength σ_u but cannot measure the material's fracture toughness.

Region B: cracks which are small enough to have some effect. However if the failure stress from these tests is used to predict toughness (without applying suitable corrections) then the resulting value of J_c will be lower than the true value.

Region C: cracks which are long enough that failure is entirely determined by the fracture toughness. J_c can be measured but σ_u cannot.

In fact, data from region B can be analysed to obtain estimates of both strength and toughness for the material, if sufficient information is available, though this is not straightforward. Several theoretical models exist for performing this analysis (which will be discussed below) but there is no general agreement on how it should be done. A useful parameter in this respect is the so-called "critical distance", L, defined as:

$$L = \frac{1}{\pi}\left(\frac{J_c E}{\sigma_u^{\,2}}\right) \qquad (2)$$

The crack length a^* is of the same order of magnitude as L, so regions A, B and C can be defined according to the value of crack length relative to L. This parameter is also important in relation to other specimen dimensions, as will be discussed further below.

This paper discusses the published literature on fracture toughness measurement of soft tissues and presents some new data from experimental tests on muscles. Our hypothesis is that most studies to date have not actually measured the fracture toughness of soft tissue material. We argue that most of the published test results fall within region A and therefore provide no information on the value of J_c. The consequences of this finding for the mechanical behaviour of these tissues is discussed.

Previous Work

This section summarises all the previous literature on fracture toughness testing of soft tissues which were able to find. The normal procedure for measuring J_c, as developed for engineering materials, is illustrated in fig.2. A crack (length a) is introduced into a sample of material (width W, thickness B), which is then loaded in tension until the crack propagates. Load may be applied uniformly along the top and bottom surfaces of the sample (known as unaxial tension) or alternatively the loading points may be located near to the edge containing the crack (known as compact tension). There are various different ways of introducing a crack into the sample before testing. A sharp notch (produced, for example, by cutting the material with a scalpel) can be used provided the notch is sufficiently long and sharp: in all work described here (including our own tests) this condition was met. Normally a "stiff" testing machine is used, in which the distance between the loading points is gradually increased at a constant rate of displacement, whilst monitoring the applied load and crack growth. The toughness J_c can be found from the load/displacement curves as shown in fig.2; if the crack grows from a length a to a larger length ($a+\delta a$) then the crack propagation energy U_c is given by the area between the loading lines for these two crack lengths. The fracture toughness J_c is found by dividing U_c by the area of new crack created, which is $B\delta a$.

All published work (summarised in Table 1) used the above approach, or some variant of it. Chin-Purcell and Lewis tested cartilage from the patella, using compact tension specimens. A finite element analysis was used to assist in estimating J_c values (Chin-Purcell and Lewis, 1996). Other workers used a similar approach to study thickness effects in cartilage (Adams *et al.*, 2003) and to measure fracture toughness in temporomandibular joint (TMJ) discs (Koombua *et al.*, 2006; Beatty *et al.*, 2008). Wu *et al* measured the toughness of the stratum corneum (the outer layer of the epidermis) loaded perpendicular to its surface, using a double-cantilever beam specimen (a type of compact tension specimen) specially designed for testing thin layers such as adhesives (Wu *et al.*, 2006b; Wu *et al.*, 2006a).

Oyen-Tiesma and Cook considered the problem of viscoelasticity, which they argued will lead to an overestimate of J_c because some of the energy under the load/displacement curve will not be available for crack propagation (Oyen-Tiesma and Cook, 2001). They applied cyclic loading and observed the amount of energy dissipated when no crack grew (i.e. the area of the hysteresis loop between the loading and unloading curves). They subtracted this energy from the energy dissipated when crack growth occurred, to find U_c. Koop and Lewis analysed this and another method for compensating for viscoelasticity (Koop and Lewis, 2003). The material used by Oyen-Tiesma and Cook was an artificially-grown collagenous material termed “neocartilage” (Fedewa *et al.*, 1998) which was expected to have similar properties to cartilage except for the absence of any preferential fibre orientation, and thus was a convenient model material for soft tissues in general.

All of the above studies used initial cracks of the order of a few millimetres in length. Stok and Oloyede (2007) used very small cracks (a=25μm and 100 μm) in the superficial layer of articular cartilage samples. They reported a sudden drop in applied load coinciding with observable propagation of the crack. They argued that conventional methods of determining J_c were not appropriate because of the large amount of crack opening and blunting before failure, and proposed a different method of estimating the crack propagation energy (Stok and Oloyede, 2007).

Purslow carried out a series of uniaxial tension tests on samples of cooked meat (bovine muscle *M.Semitendinosus*) containing cracks of various lengths (Purslow, 1985). Doran et al measured fracture toughness of skin using a novel cutting test (Doran *et al.*, 2004). The literature also contains a number of papers investigating the toughness of soft tissues. In these works however, fracture toughness was estimated in a different way, using tear tests or cutting tests in which cracks were subjected to shear forces. This so-called Mode-III fracture toughness is beyond the scope of the present paper, though it will be discussed briefly below.

Methods and Materials

Experiments were designed to supplement the test data reported above. We chose muscle tissue because it is readily available in large volumes in the form of animal meat, and because fracture toughness is a potentially important parameter since muscles suffer from sub-critical damage in use (Woodhouse and McNally, 2011). We applied tensile load perpendicular to the muscle fibre direction, to complement previous data (Purslow 1985) in which the loading was applied parallel to the fibres.

The muscle used was the porcine *psoas major*. Samples from 8 different animals were obtained from a meat supplier and stored in a freezer. They were completely thawed out before testing, which was carried out within one hour of thawing. Previous work has shown significant differences in mechanical properties between fresh and stored soft tissues (Van Loocke *et al.*, 2006), so the results presented here may not be typical of this tissue *in vivo*. However this is also a limitation in other reported studies on soft tissues. Samples were cut into normal "dog-bone" shaped specimens having a central section of constant width W and thickness B, and larger ends to aid gripping. A range of specimen dimensions W and B was used, varying from 3mm to 18mm. Sharp through-thickness cracks were introduced using a scalpel into one edge of the sample in the middle of the gauge length, the crack being perpendicular to the load axis; the crack length varied from 1mm to 5mm and some specimens were tested without a crack. All specimens were loaded in tension at loading rates of 5-15mm/min, recording the applied force continuously. Some were simply subjected to a monotonically increasing strain until failure occurred, recording the maximum stress attained. Others were tested using the method of Oyen-Tiesma and Cook described above, which involved cycling each sample from zero displacement to a maximum value, repeating the cycle four times and then increasing it to a larger maximum displacement. The specimens were continuously observed, and any crack growth was recorded, using a digital microscope. Cycles in which no crack growth occurred were used to estimate the energy dissipated viscoelastically, which could then be subtracted from the total energy dissipated during cycles of crack growth, to obtain the crack growth energy U_c. Fig.3 shows examples of the load/displacement traces for the two different types of test.

Results

This section presents our own results and also data from the literature, reanalysed in various ways. In what follows the stress given is the nominal stress, defined as the load divided by the original area of the cross section, so this will be somewhat smaller than the true stress at failure owing to reduction in the cross section during loading. It is important to note that for specimens containing a crack, we define the stress as the net-section stress. For uniaxial tensile testing this is the load divided by the area of the remaining, uncracked cross section, equal to B(W-a). This tells us the average stress in the remaining cross section. For compact tension specimens the net-section stress was calculated taking account of the bending caused by the non-uniform loading.

Fig.4 shows data from various studies, all of which used uniaxial tensile loading. The failure stress, defined as the maximum stress obtained during the test, is plotted as a function of the crack length. These data are shown as solid symbols. The data from Stok & Oloyede are shown separately on fig.5 because the crack lengths used were very small. Also shown, recorded as open symbols, are results from tests in which incremental crack growth was recorded: our own tests and those of Oyen-Tiesma and Cook. Here the stress is that required to cause crack extension, either from the original notch or, subsequently, from an existing crack. The data on neocartilage represents our re-analysis of tests from a single specimen ((Oyen-Tiesma and Cook, 2001) their fig.4).

Our own data shown in fig.4 is from tests on relatively large specimens in which the net area WB was 57-76mm^2. Specimens with smaller areas showed higher failure stresses and more scatter, as shown in fig.6 which plots the failure stress as a function of net area for all cracked specimens in our test series.

Our calculations of J_c using the Oyen-Tiesma and Cook method gave very varied results, ranging from 0.55 to 8.0 kJ/m^2. The mean value was 2.49 kJ/m^2; the standard deviation was 2.14 kJ/m^2 for n=13 specimens tested. The data showed a tendency for J_c to decrease with increasing crack extension δa, (see fig.7). A best-fit line through this data corresponded to the equation:

$$J_c = 0.73(\delta a)^{-0.915} \tag{3}$$

The exponent (-0.915) is close to (-1), suggesting a constant energy U_c, and indeed the variation of U_c values was much smaller than that of J_c, having a mean of 11.2 mJ and a standard deviation of 5.24 mJ.

Discussion

The above data all point to the conclusion that our hypothesis is correct, i.e. that the specimens tested by ourselves and others lie within region A of the plot shown in fig.1. Thus the test data can be used to estimate the material's ultimate strength, but not its fracture toughness. Values of J_c derived in this way can be expected to be less than the true value and strongly dependant on crack length and other specimen parameters.

Purslow's results on cooked meat (bovine muscle) form a particularly clear set of data showing that, despite considerable scatter in individual values, there is no tendency for the net section stress to decrease with increasing notch length. Purslow himself pointed out that there was no notch sensitivity in this material when tested parallel to the fibre direction.

The present paper shows that this is also true for muscle loaded perpendicular to the fibre direction, and for neocartilage, a material in which the collagen fibres have random orientations. The data of Stok and Oloyede on articular cartilage show a small decrease in failure stress with increasing crack length, but this is very small. Given the fourfold increase in crack length from 25 μm to 100μm one would expect, according to equation 1, that the stress would decrease by a factor of 2, but in fact it drops only by a factor of 1.14. A possible explanation for this decrease is that the crack was introduced into the superficial layer of the cartilage, which is known to be much stronger and stiffer than the underlying material. The 100μm notch would have removed a significant proportion of this layer (it being typically 150-200μm thick) so this would likely show up as a small decrease in the strength of an entire specimen. In our own test results, the net stress and the total energy U_c were both better criteria for predicting the onset of crack growth than J_c, which showed huge scatter and a tendency to increase with decreasing δa. These findings are all consistent with the idea that the material in these tests is "ignoring" the crack: failure occurs in the remaining cross section under conditions of stress and energy which are independent of the presence of the crack.

The toughness tests using compact tension specimens reported in the literature all followed the same approach, but only the paper of Koombua *et al* contained enough information to allow us to calculate the net section stress at failure. Taking account of bending, we estimated a value of 4.2MPa, which is actually considerably higher than values given elsewhere for the tensile strength of uncracked samples of the same tissue, which is of the order of 1.6MPa (Kang *et al.*, 2006; Beatty *et al.*, 2001). Our estimate may be on the high side because it does not allow for non-linear elasticity and viscoelasticity in the tissues, which might tend to smooth out stress gradients and thus reduce the maximum stress. In any case, within these limitations, it appears that failure occurred at or close to the net section tensile strength of the material.

It might be argued that since crack propagation was observed to occur in these samples, then it should be possible to use the test results in some way to deduce the energy needed for crack propagation and therefore determine the fracture toughness. The problem with this argument is that, whilst a toughness value can always be calculated, if certain conditions are not met then this value is not a material property, and will be found to vary if we vary the test conditions, such as the dimensions of the specimen. For example, if the failure stress remains constant when crack length increases, then the use of equation 1 will give toughness values which appear to increase in proportion to the crack length. There are in fact situations in which toughness really does increase with increasing crack extension, giving rise to a so-called R-curve (see for example Nalla et al (2005)). This happens because as a crack grows its growth may be impeded by the development of toughening mechanisms such as uncracked ligaments across the crack faces. This effect is not to be confused with the increase in apparent toughness with increasing crack length, which occurs when measurements are made in regions A and B of fig.1. This latter effect, which is the main subject of this paper, arises due to invalid testing conditions. If, alternatively, one estimates toughness by measuring the energy change U_c and dividing by δa, then the result (for conditions conforming to region A) will be that, since U_c is constant, J_c will appear to decrease as $1/\delta a$, as we have shown (fig.7 and equation 3). This is a kind of inverse R-curve, but again it arises merely due to invalid assumptions about the test conditions.

Fracture mechanics theory, as outlined for example in two recent books (Broberg, 1999; Taylor, 2007), defines two regions in the vicinity of the crack tip, as shown in fig.8. The *process zone* is the region close to the crack tip in which the actual process of crack advance occurs, by local straining and failure of material. The exact physical mechanism by which this occurs depends on the material and other factors and can in practice be difficult to determine. Surrounding the process zone is the *plastic zone*, a region in which energy dissipating mechanisms occur, such as plastic deformation and microdamage. Outside this zone the material in the rest of the specimen deforms elastically and reversibly, albeit with the complication of dissipative viscoelasticity in the case of soft tissues.

If the dimensions of the specimen, and in particular the crack length *a* and the remaining width (W-*a*), are much larger than the size of the plastic zone, then all the processes which contribute to, or hinder, crack propagation occur in a region which is relatively small and contained close to the crack tip. Under these circumstances the size of the process zone and plastic zone at failure (i.e. when crack propagation occurs) are constant, irrespective of specimen size, and it is relatively easy to determine the toughness of the material uniquely. If the specimen is so small that the plastic zone is of the same order of magnitude as the remaining cross section, or even expands all the way across the remaining area, then a unique toughness measurement is still possible though some precautions are required. If however the process zone size becomes similar to the specimen dimensions then it becomes very difficult to make reliable measurements. The process zone size at failure is no longer a constant and the actual physical mechanisms of failure may change.

A number of theoretical approaches have been devised to try to predict toughness and material failure under these conditions. These include the Essential Work of Fracture concept of Broberg (Wildes *et al.*, 1999), the cohesive zone approach, which attempts to model the process zone (Bazant, 2004; Hillerborg *et al.*, 1976) and the approach known as the Theory of Critical Distances which has been advocated by one of the present authors (Taylor, 2007). None of these approaches is completely able to solve the problem and work is ongoing in this field. The critical distance L (defined in equation 2 above) gives an approximate estimate of the size of the process zone at failure. When the specimen dimensions are reduced to values similar to, or smaller than, L, it is common to see significant changes in measured properties such as strength and toughness. For example, the value of L for bone has been established to be 0.3-0.4mm (Kasiri and Taylor, 2008). Fracture toughness values measured for bone show a strong dependence on crack length, for cracks several millimetres long or less (Nalla *et al.*, 2005), and fatigue strength has been found to increase considerably when specimen dimensions are reduced within the millimetre range (Taylor, 2000).

The present experimental work is the only study of soft tissue toughness to date in which all relevant specimen dimensions (width, thickness and crack length) were varied significantly. We observed a considerable increase in the stress to failure with decreasing specimen size (fig.6). Similar results have been obtained for other materials, for example, in concrete (Karihaloo *et al.*, 2003). A number of factors may contribute to this effect: one mentioned above is the reduction of the process zone size. Another related factor is the presence of pre-existing defects or weak regions in the material: a smaller volume of material under stress will be less likely to contain weak regions and therefore will, on average, tend to be stronger. Muscle, like most tissues in the body, has a hierarchical structure, including fibre bundles on the millimetre scale, linked by relatively weak connective tissues.

Table 1 shows values of the critical distance parameter L estimated from the available test data, using equation 2. This value is denoted L_{min} to reflect the fact that the true value of L will be larger than this, since we believe that most existing studies have underestimated J_c. With two exceptions, the values of L_{min} for the various tissues are similar to, or only slightly smaller than, the crack length *a*, or the remaining width (W-*a*). This confirms that the sample sizes and crack lengths used were generally too small to allow fracture toughness to be measured reliably. The first exception is the work of Wu *et al.* Their material, the stratum corneum, has a very low toughness compared to its strength. As a result the value of L is much smaller than the crack length and specimen dimensions. In this case we would expect a valid measurement of toughness to be possible, and this is confirmed by their results which show a constant value of J_c for a wide range of crack extensions (1-20mm).

The second exception is the work of Chin-Purcell and Lewis on cartilage. Their specimens showed a very wide range of behaviour; some samples (which they denoted Grade 0) failed at relatively low loads with a brittle appearance (low crack-opening displacement); other specimens (Grades 1 and 2) required more load to failure and appeared tougher, whilst in some specimens crack growth did not occur at all, the crack tip becoming very blunt during loading (Grade 3). These workers did not measure the tensile strength of their samples; the value for σ_u given in Table 1 was taken from another study on articular cartilage (Schmidt *et al.*, 1990) and so may be inaccurate. Given this proviso, the L_{min} values suggest that valid fracture toughness results would be obtained from the Grade 0 samples and possibly also from Grades 1 and 2, although the crack length is less than $10L_{min}$ in these cases, which gives cause for concern. Chin-Purcell and Lewis also measured toughness using the Mode-III tearing test, and showed that this parameter increased progressively with Grade, being five times higher for Grade 3 than Grade 0.

This paper has concentrated on identifying a problem rather than proposing a solution. In our view, the standard tests for measuring Mode-I fracture toughness will often lead to invalid results in soft-tissue materials owing to their relatively high toughness-to-strength ratios. International standards exist for these tests, which contain many useful checks for validity, but being defined for engineering materials they are often difficult to comply with when dealing with soft biological material. Some simple rules can be suggested, however, which may prevent mistakes being made which can easily be avoided. Firstly, one should test using a range of different crack lengths and specimen dimensions: if the result is a valid measurement of material behaviour it should be independent of these parameters, though one should be aware of the existence of inherent size effects such as the R-curve. Secondly, one should measure the tensile strength using uncracked specimens and compare this to the stress which was needed to cause failure in the cracked specimens; this will give a clear idea of where in fig.1 the results lie. Thirdly, the critical distance parameter L provides a useful guide: for a valid result, the crack length and all other specimen dimensions should be much less than L. Finally, one should consider whether cracking, and in particular mode-I crack extension, is a failure mode which actually happens in this tissue *in vivo*; if not, even a valid result will be of little value.

An interesting example of a different approach to Mode-I toughness testing, and one which has a specific relevance, is the work of Doran *et al*. They devised a test in which a sharp blade is used to cut a piece of tissue which is already being stretched (Doran *et al.*, 2004). This allowed them to measure the fracture toughness in Mode-I whilst applying only modest stresses to the material: they estimated that only 7% of the energy for crack propagation came from the material, the rest coming from the force in the blade. More work would be needed to check the validity of their results, but the approach seems promising and has a direct application in the cutting of skin during surgery, etc.

Detailed discussion of the Mode-III tearing test is beyond the scope of this paper. We can briefly note that this test avoids some of the problems of the tensile test, though the results may still be affected by some of the experimental parameters, especially specimen thickness, and crack tip blunting. This test is measuring essentially a different property: the resistance of the material to shear forces, so it would be expected to give different values of toughness from those obtained in the tensile test anyway. Given that tissue *in vivo* is loaded with a complex mixture of tensile, compressive and shear forces, it is useful to have information about both kinds of toughness.

Even though, in our opinion, most of the existing studies have not been able to determine the toughness of soft tissues, nevertheless these findings are useful in demonstrating that these materials have a high defect tolerance. In Purslow's tests, cracks as long as 15mm did not reduce strength, except in so far as they reduced the load-bearing area of the sample. This kind of extreme defect tolerance is known to occur in highly fibrous materials, i.e. materials with a very strong preferential fibre orientation, when loaded parallel to their fibre direction. Cooked meat shows more anisotropy in its mechanical properties than fresh muscle tissue (Purslow, 1985). If the bonding between fibres is relatively poor, the material will be unable to transmit shear stress from one fibre to the next, so stress will not be able to concentrate at the tip of a crack or notch: the material functions essentially as a series of independent fibres.

More surprising is the high level of defect tolerance displayed in the other materials reported above: cartilage, neocartilage and our own results on muscle loaded perpendicular to the fibre direction. Cracks several millimetres long could be introduced without reducing the net-section stress to failure. Most soft tissues will not experience cracks any longer than this *in vivo*, so the implication is that their defect tolerance is as large as will ever be necessary for practical purposes. Whilst we don't yet know the fracture toughness of these materials, we can suppose that it is high enough, relative to material strength, to prevent crack extension for any cracks which may occur, at any loadings which may arise in use. The only possible exceptions amongst the tissues tested so far were the stratum corneum and the patellar cartilage. Interestingly, the fact that patellar cartilage is sensitive to small cracks was established by Flachsmann *et al*. They subjected cartilage-on-bone samples to compression using a large (8mm diameter) cylindrical indenter (Flachsmann *et al.*, 2006). This type of loading caused tensile strain in the superficial layer of the cartilage. They found that introducing cracks about 1mm long reduced the compressive strength to less than half of the value measured for uncracked samples. This finding supports the view expressed above that the results of Chin-Purcell and Lewis may indeed be a valid measurement of fracture toughness for articular cartilage, and agrees with the generally held view that cartilage failure *in vivo* involves progressive growth of defects. A complication here is that the superficial cartilage layer seems to have much greater defect tolerance, according to the results of Stok and Oloyede analysed above. Chin-Purcell and Lewis tested cracks growing inside the articular cartilage, not in the superficial layer. The cracks made by Flachsmann *et al* were created in the superficial layer but, being about 1mm in length, almost certainly penetrated into the underlying cartilage. Thus it may be that cracks only weaken cartilage once they breach the superficial layer.

Finally, it should be noted that cracks may form and grow in tissues by two time-dependant mechanisms: fatigue and creep. Cyclic loading causes fatigue cracking to occur in most materials at stresses less than the material's ultimate strength and these cracks can grow at energies less than J_c. Cracks can also slowly extend due to flow-related creep mechanisms.

There has been almost no work on fatigue and creep cracking in soft tissues, which is probably crucial for our understanding of how damage develops in these materials. The present paper has also been limited to testing at relatively slow loading rates and so does not consider the toughness of these materials under impact loading, which is also a crucial subject for further study.

Conclusions

1) In most cases, the previous studies on soft tissue materials have not been able to measure their fracture toughness. Owing to the use of small specimen sizes and crack lengths, failure occurred in the test specimens at the material's ultimate tensile strength, thus no information on toughness can be obtained from the results.
2) The above conclusion applies also to our own new results on muscle tissues loaded perpendicular to the fibre direction. The measured J_c value was a strong function of crack growth increment, whilst the failure stress and energy were both constant, within a normal range of scatter, when specimen size was kept constant.
3) The critical distance parameter L, was found to be large with respect to the crack length and the remaining uncracked width in our specimens and in most previous work: this explains the strong effect of specimen size in our data and provides further support for our hypothesis.
4) Even though most of the available toughness data must be regarded as invalid, it does serve to illustrate the very high defect tolerance of many soft tissues. Toughness appears to be as high as would be needed to prevent the propagation of any defects that might occur *in vivo* when subjected to short term loading. The response of these tissues to other failure modes involving crack growth, especially fatigue and creep, remains to be determined.

Table 1: Summary of all the data analysed.

Tissue type	Source reference	Specimen type	Young's Modulus E (MPa)	Failure Stress σ_f (MPa)	Apparent Toughness J_c (kJ/m^2)	Thickness B (mm)	Width W (mm)	Crack Length *a* (mm)	Minimum critical distance L_{min} (mm)
Porcine muscle	Present study	Uniaxial tension	0.4	0.15	2.49	3-15	4-18	0-5	14.1
Cooked bovine muscle	Purslow (1985)	Uniaxial tension	See note*	0.47	See note*	5	30	0-15	31.1
Cartilage (superficial layer)	Stok & Oloyede (2007)	Uniaxial tension	See note*	1.5	See note*	0.5-2.5	1-5	0.025 and 0.1	0.11
Cartilage GRADE 0	Chin-Purcell and Lewis (1996)	Compact tension	7.03	8.6	0.14	0.2	1.5	0.2	0.0042
Cartilage GRADE 1	Chin-Purcell & Lewis (1996)	Compact tension	8.93	8.6	1.46	0.2	1.5	0.2	0.056
Cartilage GRADE 2	Chin-Purcell and Lewis (1996)	Compact tension	6.62	8.6	1.16	0.2	1.5	0.2	0.033
Neocartilage	Oyen-Tiesma & Cook (2001)	Uniaxial tension	2.13	0.42	0.4	0.067	5-6	1.7-2	1.54
TMJ disc	Koombua *et al* (2006)	Compact tension	2.17	1.5	5.86	2	12	3	1.80
Stratum corneum	Wu et al (2006)	Double Cantilever Beam	13	0.55	0.0037	10	40	0-20	0.051

Notes

*J_c values were not calculated in these papers. L_{min} was calculated from an estimated K_c value using the experimental failure stress and crack length.

Where a range of material property values was measured, the value quoted here is the average.

Figure Captions

Figure 1: The effect of crack length on the applied stress to failure. For long cracks failure occurs at stress σ_f which is determined by the fracture toughness J_c and the crack length (Region C). For very short cracks failure occurs at a constant stress σ_u, the material's ultimate strength (Region A). Experimental data, typified by the thick line, also show an intermediate region in which the failure stress is lower than either σ_f or σ_u.

Figure 2: The test procedure for determining J_c. A specimen containing a crack is subjected to an applied displacement whilst measuring load. If the crack extends from length a to length ($a + \delta a$) then the fracture energy U_c is found from the area between the loading lines for these two lengths. J_c is given by dividing U_c by the new crack area $B\delta a$.

Figure 3: Typical load/displacement traces from our experiments. Above: monotonic loading to failure for five notched samples. Below: Loading/unloading traces for a notched sample, under conditions of crack extension and no crack extension; the latter trace has been shifted along the displacement axis for ease of viewing.

Figure 4: Data from the present work (muscle), the work of Purslow (1985) (cooked meat) and that of Oyen-Tiesma and Cook (2001) (neocartilage). Solid symbols show the specimen failure stress (i.e. maximum net-section stress during the test); open symbols show the stress at which observable crack growth occurred.

Figure 5: Data from Stok and Oloyede (2007) on small cracks in the superficial layer of articular cartilage. Failure stress (at which crack propagated across the entire thickness of the superficial layer) as a function of crack length.

Figure 6: Failure stress as a function of specimen size, defined as the area of the remaining cross section (W-a)B, for all our tests on cracked specimens of muscle tissue.

Figure 7: Calculated values of J_c for our muscle tissue as a function of the amount of crack extension δa.

Figure 8: Cracked bodies contain a "process zone" in which failure processes occur when the crack grows, and a surrounding "plastic zone" in which energy dissipating mechanisms occur.

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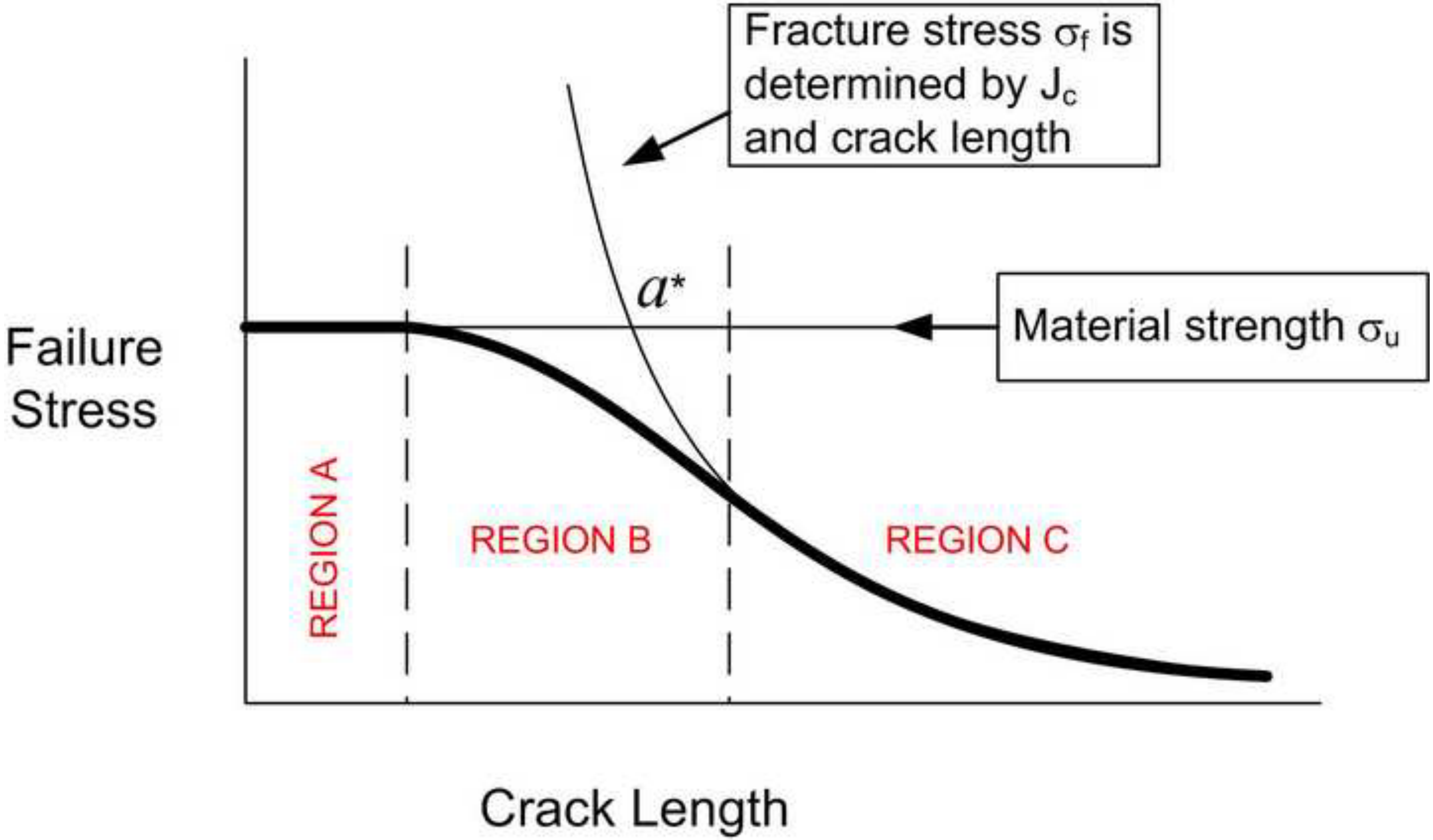

Fracture stress σf is
determined by Jc
and crack length
Material strength σu
a*
Failure
Stress
REGION A
REGION B
REGION C
Crack Length

Figure 2

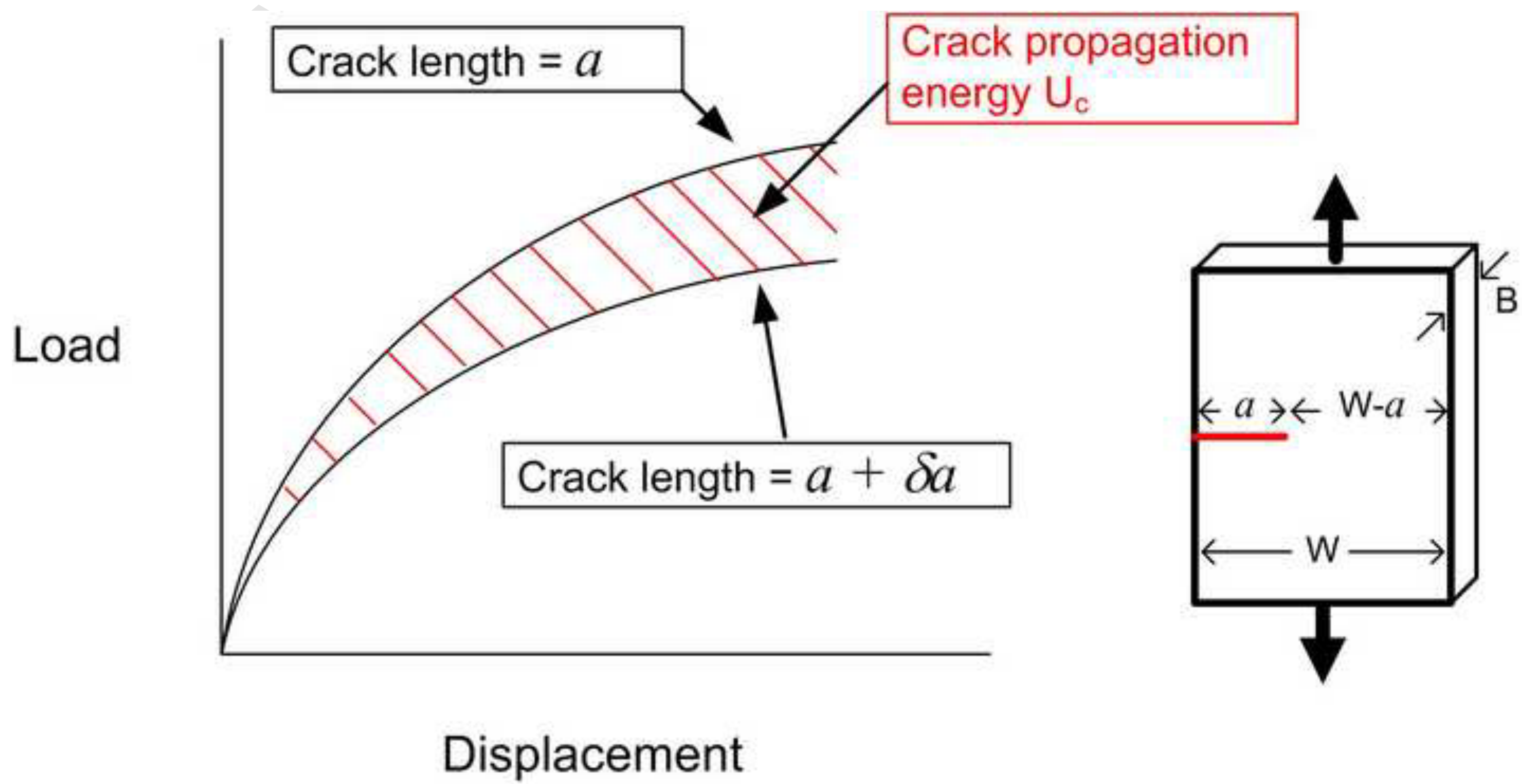

Load
Displacement
Crack length = a
Crack propagation energy U_c
Crack length = $a + \delta a$
B
a
W-a
W

Figure 3
Click here to download high resolution image

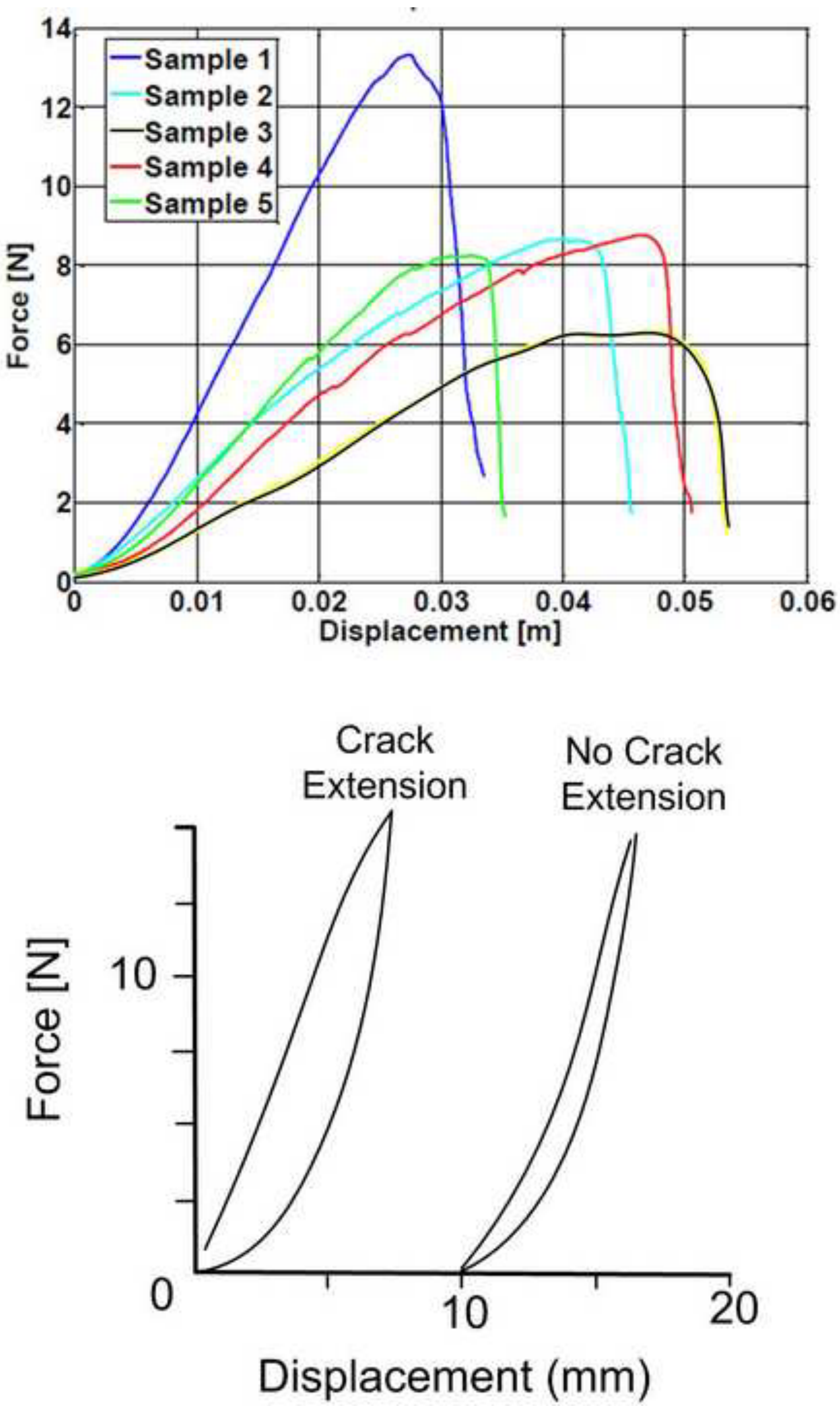


Figure 4
Click here to download high resolution image

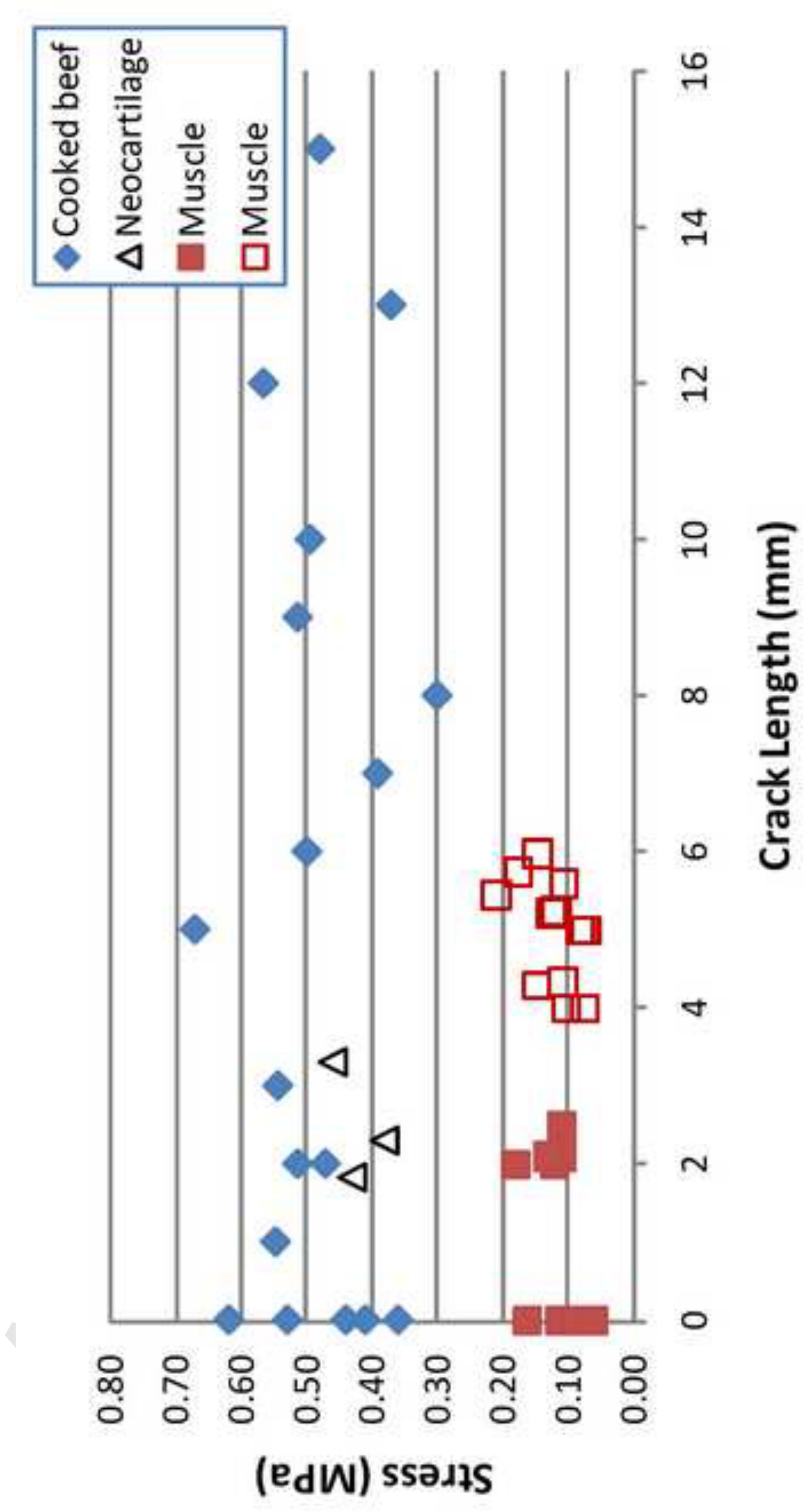


Figure 5

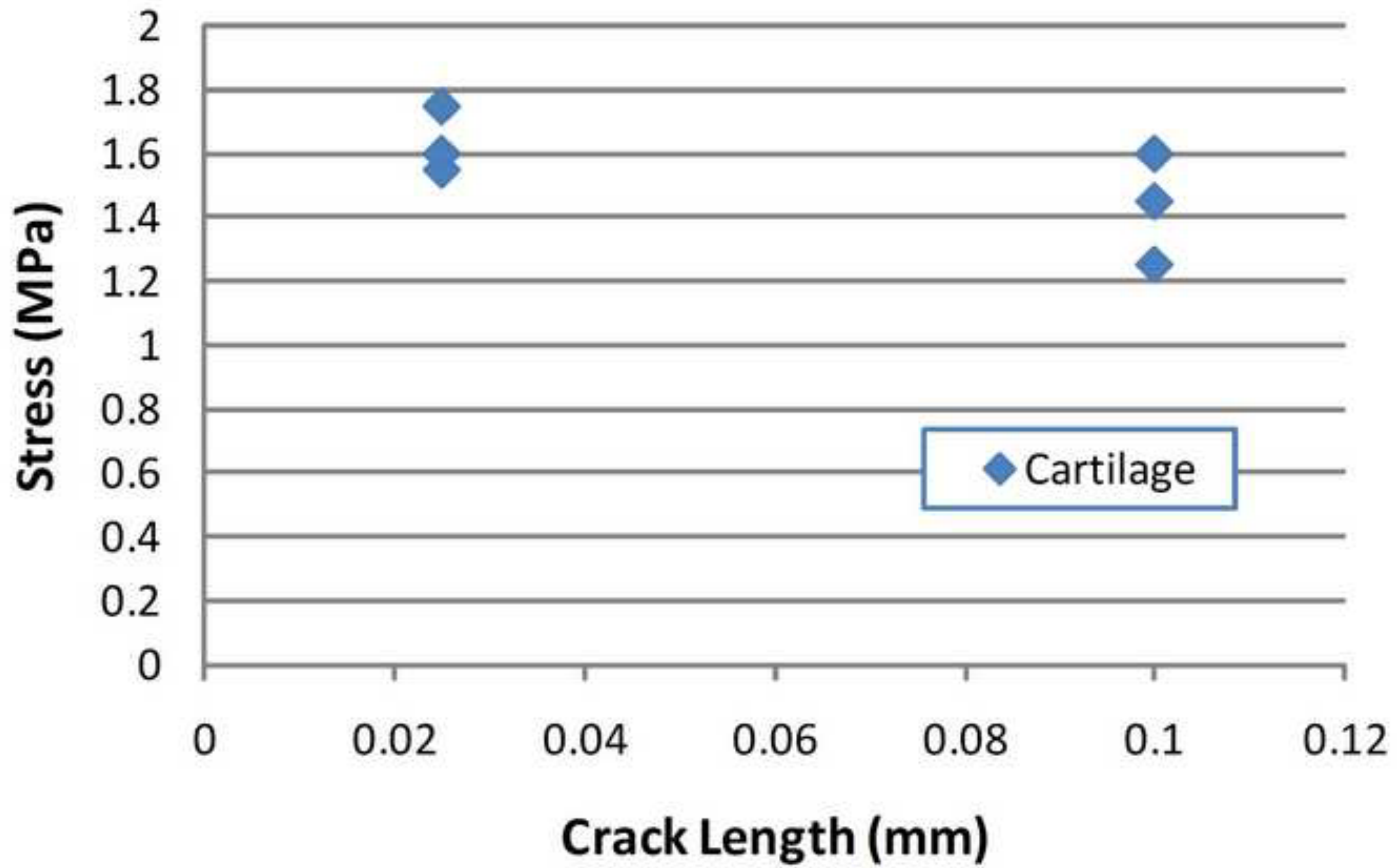
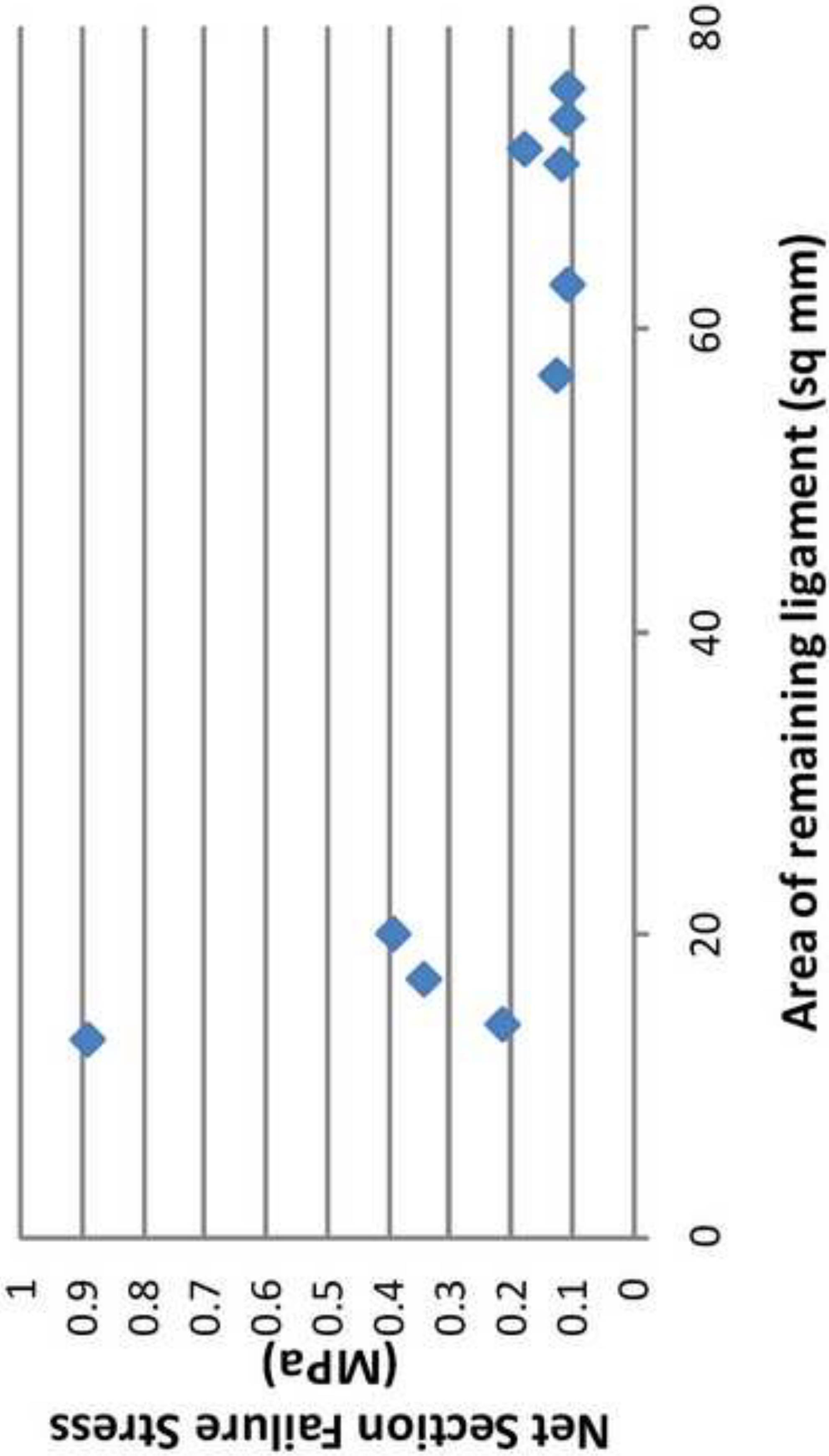

Stress (MPa)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.02
0.04
0.06
0.08
0.1
0.12
Crack Length (mm)
Cartilage

Figure 6


Net Section Failure Stress (MPa)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
Area of remaining ligament (sq mm)

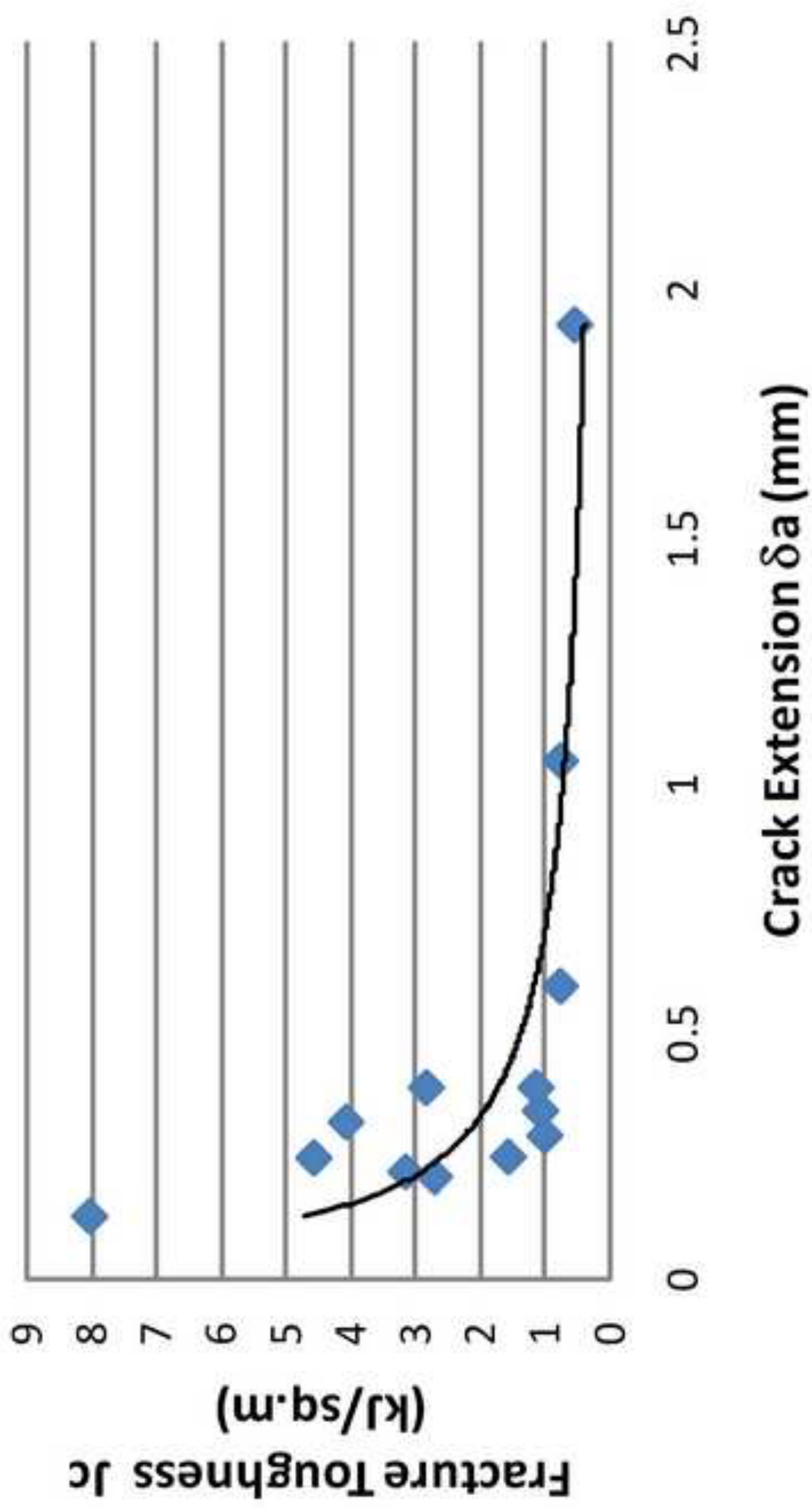

Fracture Toughness Jc
(kJ/sq.m)
0
1
2
3
4
5
6
7
8
9
0
0.5
1
1.5
2
2.5
Crack Extension δa (mm)

Figure 7

Figure 8