LA-UR-17-21555
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Title: The Two-Way Relationship between Residual Stress and Fatigue/Fracture

Author(s): Prime, Michael Bruce

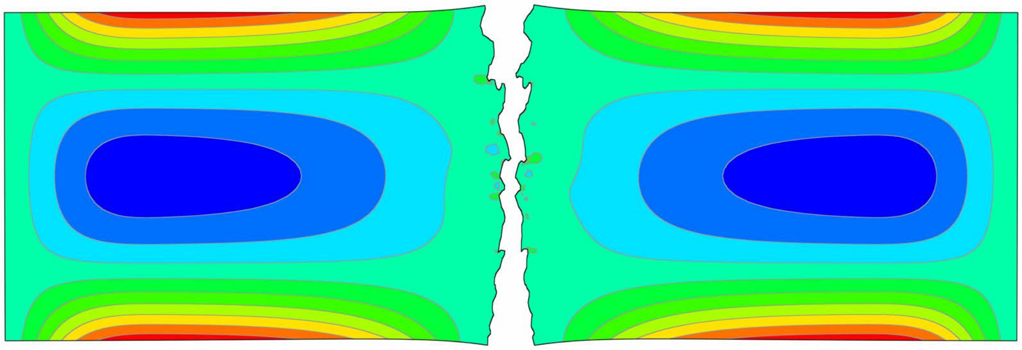
Intended for: SEM Conference and Exposition on Experimental and Applied Mechanics,,
2017-06-12 (St. Louis, Missouri, United States)

Issued: 2017-02-24

Reference:
Prime, M. B., 2018, "The Two-Way Relationship Between Residual Stress and Fatigue/Fracture," Fracture, Fatigue, Failure and Damage Evolution, Volume 7: Proceedings of the 2017 Annual Conference on Experimental and Applied Mechanics, J. Carroll, S. Xia, A. M. Beese, R. B. Berke, and G. J. Pataky, eds., Springer International Publishing, Cham, Switzerland, pp. 19-23.

DOI: 10.1007/978-3-319-62831-8_4

https://doi.org/10.1007/978-3-319-62831-8_4



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The Two-Way Relationship between Residual Stress and Fatigue/Fracture

Michael B. Prime
MS A142, Los Alamos National Laboratory, Los Alamos, NM 87545 USA.

ABSTRACT

Most mechanicians are aware that residual stresses affect fatigue and fracture. Few are aware of the full extent of the effects residual stress have on myriad aspects of those and other structural processes AND of the reverse relationship: fracture concepts are hugely intertwined with residual stress measurements. This talk first reviews the straightforward effect that residual stress has: it acts just like an external load and, depending on the sign, accelerates or retards failure processes. The talk then describes one exemplar less well-known effect: residual stress can make it very difficult to measure true material properties like fracture toughness. The talk then describes the influence of fracture concepts, most notably the mode I stress intensity factor K_I, on residual stress measurement. A short and elegant derivation reveals that incremental slitting measurement strain data can be converted to residual stress profiles using a K_I analysis and a conceptually simple calibration factor that is independent of the stress distribution. The talk next shows that several error sources for slitting and contour method stress measurements can be directly correlated with the K_I caused by residual stress. The talk then lays out Bueckner's superposition principle, the most powerful but misunderstood and mistrusted tool for analyzing stress fields around cracks. Originally developed for fracture mechanics, Bueckner's is used to calculate the K_I from residual stresses and to calculate calibration coefficients for hole drilling and slitting. More notably, the contour method for measuring residual stress is a direct experimental embodiment of Bueckner's principle. In fact, we review an experimental demonstration that misfit measurements between mating fracture surfaces can be used to calculate the residual stresses that existed prior to the fracture.

Keywords: residual stress, fracture mechanics, superposition, stress intensity factor

RESIDUAL STRESS INFLUENCE ON FATIGUE AND FRACTURE AND PROPERTIES

Residual stresses are the stresses present in a part free from external load, and they are generated by virtually any manufacturing process [1,2]. They can be particularly insidious because they are ubiquitous, offer no external evidence of their existence, and they are difficult to predict or measure.

The most straightforward relationship between residual stress and failure processes is that residual stresses add to applied loads and contribute to many material failure processes like fatigue, fracture, and stress corrosion cracking [3-8]. The relationship can illustrated using the mode I stress intensity factor K_I used for fatigue and fracture and the standard fracture criteria:

$$(K_I)_{applied} + K_{Irs} > K_{Ic} \qquad (1)$$

where K_{Irs} is the residual stress contribution to K_I. For brittle fracture, the sum of the K_I's from residual stress and applied must exceed the fracture toughness K_{Ic}, a material property, for failure. The contribution may be beneficial in the case of compressive residual stress (negative K_{Irs}) or harmful in the case of tensile stress. For fatigue, residual stress acts as a mean stress as compared to an alternating stress and therefore has more impact in fatigue crack growth situations [9-11] than high-cycle fatigue.

A related but less well-known residual stress effect is the "contamination" of material property measurements [12-16]. We continue our example using fracture toughness. In fracture toughness testing, a load is applied to a test coupon and the applied K_I at fracture is assumed to be the fracture toughness:

$$(K_{Ic})_{apparent} = (K_I)_{applied} \qquad (2)$$

However, test coupons often contain residual stress. When the crack is introduced into a fracture coupon, the release and redistribution of residual stress results in a K_{Irs}. Combining and rearranging equations (1) and (2) we get

$$\left(K_{Ic}\right)_{apparent} = \left(K_{I_c}\right)_{actual} - K_{Irs} \qquad (3)$$

Which shows that the apparent, “measured” fracture toughness can be significantly in error. Such results confound the development of fracture resistant alloys and transferring coupon data to the prediction of structural failure.

INFLUENCE OF FRACTURE CONCEPTS ON RESIDUAL STRESS MEASUREMENT

The incremental slitting method for measuring residual stress, also known as crack compliance, is a powerful and widely used method [17,18]. By incrementally introducing a narrow slit and measuring relaxed strain at each increment of slit depth, it is possible to precisely determine a depth profile of residual stresses. Through a simple derivation, it can be shown that the incremental slitting data can be used to calculate the K_{Irs} more simply and directly than one can calculate the residual stress [19-21]:

$$K_{Irs}(a) = \frac{E'}{Z(a)} \frac{d\varepsilon}{da} \qquad (4)$$

where Z(a) is a geometric calibration factor that is independent of the stress distribution. One can then calculate the residual stress from K_{Irs} as has been recognized for a long time [22].

Like all relaxation methods, slitting relies on the assumption that the stresses relax elastically after material removal [2]. It turns out that slitting method errors due to plasticity can be better analyzed and predicted using K_{Irs} than using simple stress magnitudes [23].

Maybe the most powerful and pervasive contribution of fracture mechanics to residual stress is a superposition principle that immensely simplifies calculations. A problem seemed intractable at the dawn of fracture mechanics before the wide availability of finite element modeling. In a body under stress (applied stress and/or residual), the growth of a crack (or in the introduction of a slit) causes stresses to be released on the face of the crack and the subsequent redistribution of all stresses in the body. A further increment in crack length would then release not the original residual stresses but now the post-redistribution stresses. How to keep track of all that redistribution and correctly calculate everything? In 1958, Hans Bueckner proved the superposition principle that allows one to calculate K_I and deformations using only the *original* stresses on cut plane [24].

Fig. 1 shows an illustration of Bueckner’s principle as applied to residual stress. The first published illustration of Buckner’s principle in this form was given by Barenblatt [25] although Paris also published a similar figure apparently independently of Bueckner [26]. In Fig. 1, A is the body in its original state with residual stresses and this is taken as the undeformed state. B is the deformed state of the body after the introduction of a crack. This is the state where the fracture mechanics community would want to know K_I, and the residual stress community would want to know the deformations. One can get back the A state by adding the state in B to a state (stresses and displacements) calculated by applying the original stresses on the cut plane as surface tractions to a cracked but unstressed and undeformed body. The second line of Fig. 1 shows then that by simple re-arrangement B can be found by adding the original state A to a calculated state where one applies the *original residual stresses along the crack plane* to a the faces of the crack. Since the state A is undeformed and has a $K_I = 0$ (no crack so no stress singularity), only the calculated state is needed! This principle is so simple and non-intuitive that it is widely misunderstood and some mistakenly believe it does not calculate the redistribution correctly [27].

Conversely, Bueckner’s is used incorrectly sometimes. For considering local plasticity effects in residual stress measurements, Bueckner’s is the wrong approach because the vonMises stress is not zero in state A, so one cannot just use C by itself to examine the cracked state. Instead of using Bueckner’s, one should initialize the full residual stress field [23]. In either case (Bueckner’s or initial stress), one also has to extend the crack, slit or hole incrementally in order to capture the path dependence of plasticity effects.

Bueckner's principle is used ubiquitously in residual stress measurements. Because of the stress redistribution issue, an inverse procedure is necessary to calculate a residual stress profile from measured strains [28,29]. To perform the inverse, one needs calibration coefficients that tell you the strain that would be measured if you knew the residual stress. Those coefficients are calculated using Bueckner's principle for the slitting method [17], hole drilling [30,31], and other relaxation methods.

The one relaxation method that avoid the cumbersome inverse calculation does so by further exploiting Bueckner's principle [32-34]. In the contour method, a part is cut in two and the shape (contour) after cutting is measured on the cut surface (B in Fig. 1 but with the part cut all the way through) and then applied in a calculation to the cut surface (C in Fig. 1 but displacements instead of stresses) to calculate the original residual stresses directly. In another relationship with fracture, we also find that bulge and plasticity errors with the contour method are best estimated using K_{Irs} than using simple stress magnitudes [35-37].

A final application of Bueckner's principle allows one to solve what almost sounds like an unsolvable problem. With no measurements or data prior to a fracture, is there any way to take the failed part and "measure" what the residual stresses were prior to fracture on the plane of the fracture? Since the stresses normal to the cut plane were relaxed by the fracture, it would seem there is nothing left to measure. But if stresses were relaxed by the fracture, there will be a geometric mismatch between the fracture surfaces, as illustrated in Fig. 2, and the mismatch is sufficient to uniquely calculate the original residual stresses on the cut plane. This method was demonstrated experimentally on fractured aluminum forging and independently validated using neutron diffraction [38].

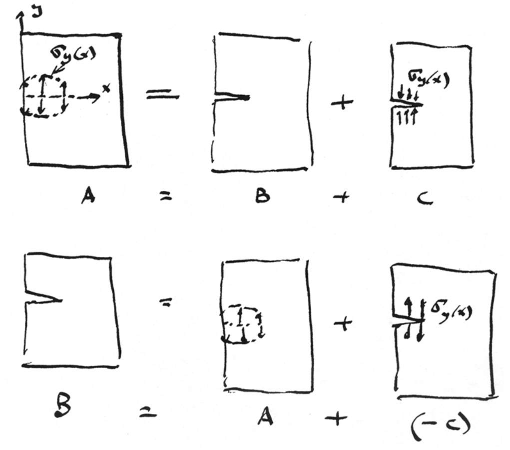

Fig. 1 An illustration of Bueckner's superposition principle from a paper copy of Iain Finnie's course notes at U.C. Berkeley [39]

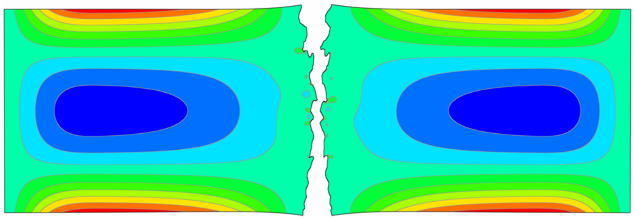

Fig. 2 The mismatch between otherwise mating fracture surfaces can be used to calculate the residual stresses that existed prior to the fracture. Blue represents compressive residual stress and red is tensile.

ACKNOWLEDGEMENTS

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