Fatigue Life Assessment of a Novel Mobile Phone Hinge

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Abstract

An innovative hinge structure of a flip-cover mobile phone is currently under development, and the corresponding fatigue life assessment is therefore anticipated. A finite element analysis is carried out to investigate the response of the hinge under the cyclic loading conditions. The critical plane approach, linking to the baseline measurements, is adopted to construct relationships between damage parameters and fatigue lives. The submodelling technique is also implemented into the analysis for the detailed examination of the critical region. Furthermore a finite volume weighted averaging scheme is used for the reasonable life prediction here. The damage criterion proposed by Socie et al. might give fair fatigue life estimations.

1. Introduction

In order to simplify the part-assembly procedures, flexible printed circuit boards (FPCBs) instead of cables are intended to be applied to a hinge of a flip-cover mobile phone. A novel structure with a slotted cylindrical tube for the assembly requirement is presently under development. Load-carrying capacity of the slotted component could be dramatically reduced, and the associated fatigue life then should be evaluated. A systematic methodology of life prediction utilizing numerical analysis is thus proposed here.

Wei and Tim [1] studied flexible hinges of piezoactuator displacement amplifiers under various loading conditions, and explored relationships between the endurance limit and the maximum equivalent stress. Kosei et al. [2] investigated effects of lubrication of a laptop hinge on the prescribed torque. They found that traction control of friction slider pair is evidently beneficial to the reliability of the hinge. Huang [3] conducted a finite element analysis for a bracket of the laptop hinge structure. Simulation results showed that the location with the maximum equivalent stress coincides with the observed failure site. Kuo [4] designed a new latchless leaf-type hinge. Effects of several parameters on the fatigue life were examined using the Taguchi method. Kuo [4] concluded that the lubrication plays an important role on the life cycle. Su [5] investigated effects of different materials and surface conditions on tribological behaviors of the laptop hinge under various lubrication conditions. Experiments further showed that the roundness of bearing part obviously dominates the fatigue life of the hinge.

A widely-used mechanical analysis commercial package, ABAQUS (Hibbitt et al. [6]), is adopted to investigate the response of the mobile phone hinge under the cyclic open/close procedures of a cover. The critical plane approach is applied to assess the fatigue life of the hinge. An element with the maximum equivalent stress/strain is identified as the so-called critical element. In order to accurately capture the stress/strain response of the critical element, and further more reasonable fatigue life, the submodelling technique combining with a finite volume weighted averaging scheme is also incorporated into the simulations.

2. Finite Element Analysis

A new-developed hinge is primarily composed of four components, namely, a slotted hollowed cylinder, a non-linear spring, a positioning convex sleeve, and a positioning concave sleeve. Torque loadings prescribed on the convex sleeve drive it to climb along the slant of the concave sleeve. The spring would push the convex sleeve down to grooves while the rotational angle reaches -90°, 90°, and 180°.

Stainless steel is adopted for the cylinder and two sleeves, and the corresponding mechanical properties are listed in Table 1. Both bottoms of the cylinder and the concave sleeve are restrained with all degrees of freedom. One complete cylic loading condition is defined as the convex sleeve first rotating 90° clockwisely followed by rotating 90° couterclockwisely. Friction behavior between all contact interfaces is usually related to the associated lubrication and cycle numbers. For simplicity, Columb’s law with a constant coefficient of friction is used in the analysis. A second-order element of C3D10M is chosen for the current elastic-plastic analysis. Note that much higher mesh densities are set around contact interfaces between convex and concave sleeves.

Table 1 Mechanical properties of stainless steel

Elastic Modulus (*GPa*)	Yield Stress (*MPa*)	Poisson’s Ratio
220	251	0.3

Numerical results indicate that the critical element with the maximum equivalent stress locates at the inner side of the cam ring as marked by a square region in Fig. 1. Stabilized stress-strain hysteresis loops of the critical element can be reached after 3 cyclic loading/unloading procedures here. Stress and strain responses of the critical element are then applied to the computation of damage parameters defined below.

The submodelling technique is commonly employed to obtain reasonable numerical results using relatively moderate computational resources. Boundary conditions prescribed on the submodel are calculated fields (such as displacement, loading, temperature, and energy) extracted from the associated full model. A submodel covering the critical element of the full model is chosen and highlighted by a square region shown in Fig. 2. Three-level submodels are adopted while finer mesh size is assigned to higher level submodel in the current study.

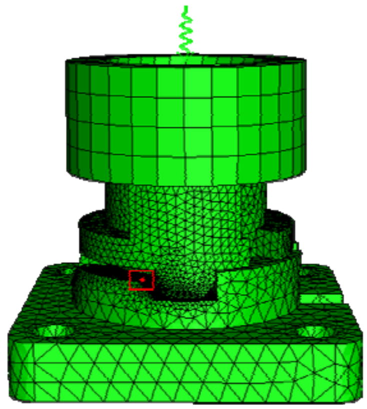

Fig. 1 Indication of the critical element in the full model

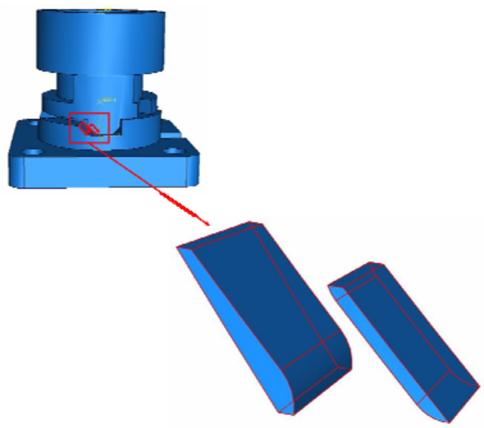

Fig. 2 Selection of the submodel

3. Fatigue Life Assessment

For mechanical components under cyclic loading conditions, the stress-based and the strain-based approach are generally used to evaluate the corresponding fatigue life. The stress-based approach is generally applied to the assessment of high cycle fatigue life for the component in which the induced stress is within the elastic range of the associated materials. On the other hand, the strain-based approach is usually utilized to estimate the low cycle fatigue life of the component having local plastic strain. This approach, for example, has been commonly employed into the electronic package industry to investigate the reliability of encapsulated structures under the temperature cycling test (for example, see Wang et al. [7], Teo [8], and Liao and Tsai [9]). Several strain-based multiaxial damage models were further developed for correlations of fatigue life to various types of strain range (for example, see Fatemi and Socie [10], Socie [11], and Chu [12]).
Ruiz et al. [13] investigated the fretting behavior of the dovetail joint between blade and disk in a typicall gas-turbine configuration. They advised a parameter combining fretting damage and peak stress for the life assessment of the joint. Iyer et al. [14] evaluated effects of five mechanical parameters controlling fretting

wear damage on a pinned connection using a two-dimensional finite element model. Sraml et al. [15] examined the crack initiation and fatigue life of a component under cyclic rolling-sliding conditions. Influences of contact friction on critical material point sites were also explored. Sum et al. [16] incorporated the critical plane approach to examine fatigue behaviors of aeroengine spline couplings, susceptible to both fretting and plain fatigue cracking, under the torque loading conditions. The spline life and crack initiation were fairly predicted compared with the corresponding measurements. Liao et al. [17] investigated fatigue behaviors of a laptop computer hinge using the critical approach. They stated that life based on the damage criterion proposed by Socie et al. is in relatively fair agreement with that based on the associated experimental measurements.

In recent years, the critical plane approaches have been commonly used and successfully predicted the fatigue lives of various structural components under multiaxial loading conditions (for example, see Chu et al. [18] and Yip and Jen [19]). The critical plane approach of the fatigue analysis originates from the observations of the fatigue crack, which commonly occurs either on the maximum normal stress/strain plane or on the maximum shear stress/strain plane. The material is assumed to fail on the plane accumulating the largest amount of damage based on a given criterion. Failure defined here does not indicate the rupture of the cylinder in which cracks possibly exist though. The argument that nucleation and/or growth of the fatigue crack deteriorate load-carrying capacity of the cylinder nonetheless coincides with the physical basis of the critical plane approach.

Smith et al. [20] proposed a damage criterion in which the normal strain amplitude and the mean stress effect are included to estimate the fatigue lives. It is worthy to be noted, for ductile materials, that the tensile mean stress is usually detrimental to the fatigue lives while the compressive one is beneficial to the fatigue lives. Brown and Miller [21] incorporated the shear strain amplitude and the normal strain amplitude on this shear plane in a damage model to enhance the accuracy of the fatigue life predictions under certain loading conditions. Lohr and Ellison [22] stated that the crack growth propagating through the thickness dominates the fatigue behavior. They therefore suggested a criterion including the shear strain amplitude driving the crack through the thickness and the normal strain amplitude on this shear plane as well. Simultaneously considering contributions of the shear strain amplitude, the normal strain amplitude acting on the shear plane, and normal mean stress acting on this plane to the damage accumulation, Socie and Shield [23] and Socie et al. [24] further modified the Brown and Miller criterion [21] to improve the fatigue life estimations under several proportional and non-proportional loading paths. Fatemi and Socie [10] and Fatemi and Kurath [25] proposed a damage parameter as a function of the shear strain amplitude and the normal stress amplitude on this shear plane. They concluded that the new criterion gives better fatigue life predictions under various out-of-phase loading histories.

Wang [26] and Wei [27] examined fatigue lives of stainless cylinders with various grooves under the multiaxial non-proportional loading conditions. Comparing with experimental results, they found that the accuracy of the fatigue life prediction is strongly related to the loading type. Smith-Watson-Topper criterion [20] dominated by the principal strain amplitude, for example, is appropriate for the fatigue life prediction of a structure subjected to the axial loading. The hinge structure is primarily under the torque conditions, the damage criterion controlled by shear strain amplitude therefore should be used here.

Three damage criteria, namely, Brown and Miller criterion, Socie et al. criterion, and Lohr and Ellison criterion, are employed in the analysis. Brown and Miller [21] proposed that both shear strain amplitude γ_a and normal strain amplitude on this shear plane ε_n are harmful to the fatigue lives. The damage parameter P_{BM} is thus in a form of

$$P_{BM} = \gamma_{\max} + K\varepsilon_n \tag{1}$$

where a constant K is selected to be 0.5. Since the tensile mean stress perpendicular to the plane with a crack usually accelerates the crack growth, Socie et al. [24] introduced the normal mean stress σ_{nm} into their damage parameter P_S as

$$P_S = \gamma_{\max} + \varepsilon_n + \frac{\sigma_{nm}}{E} \tag{2}$$

here E represents the elastic modulus of the material. Lohr and Ellison [22] suggested the damage parameter P_{LE} as

$$P_{LE} = \gamma^* + 0.4\varepsilon_n^* \tag{3}$$

where γ^* and ε_n^* indicate the shear strain amplitude driving the crack through the thickness and the normal strain amplitude on this shear plane, respectively.

Searching procedures of the critical plane with the largest amount of damage for all criteria are the same as those reported in Chu et al. [18] and Chu [12].

In the analysis, Singularity phenomenon with high stress/strain states could be induced due to the abrupt geometry change of the structure. Akay et al. [28] proposed the volume weighted averaging scheme over the entire material domain to characterize the singular point. However, the stress/strain response of the structure could be underestimated using such the averaging approach. Cheng et al. [29] then further modified the volume weighted averaging scheme, defined in Eq. (4), to manage the strain response in a rather limited range. They stated that the chosen domain at least contains the element with the largest equivalent strain, and the volume weighted averaging strain in a specific zone $\tilde{\varepsilon}$ should be relatively insensitive to the mesh density.

$$\tilde{\varepsilon} = \sum_{e=1}^{n_0} \int_{\Omega_e} \varepsilon_e d\Omega / \sum_{e=1}^{n_0} \int_{\Omega_e} d\Omega$$
(4)

Here n_0 is element numbers in the specified volume, ε_e is the strain of the *e*th element, and Ω_e is the volume of the *e*th element.

The fatigue life of the hinge structure could be too conservative once the damage parameter directly based on the critical element is used. We therefore implement the finite volume weighted averaging scheme into the calculations to obtain the reasonable damage parameter and further the corresponding fatigue life as well. Three various regions are designated for each level submodel as shown in Fig. 3. Stress/strain states of each region are first evaluated via the finite volume weighted averaging scheme, and different damage parameters are then subsequently obtained. Relationships between damage parameters and mesh numbers of three submodels based on Brown and Miller criterion, for example, are shown in Fig. 4. Symbols in the figure from left to right represent the data from the first-level, the second-level, and the third-level submodel, respectively. It shows that the damage parameter based on Regions 1 and 2 substantially increase with respect to the mesh number. However, the damage parameters based on Region 3 nearly remains a constant value as the mesh number increases. According to the arguments in Cheng et al. [29], the second-level submodel with Region 3 might be able to provide the appropriate damage parameter. A flow chart of the fatigue life assessment procedures is displayed in Fig. 5.

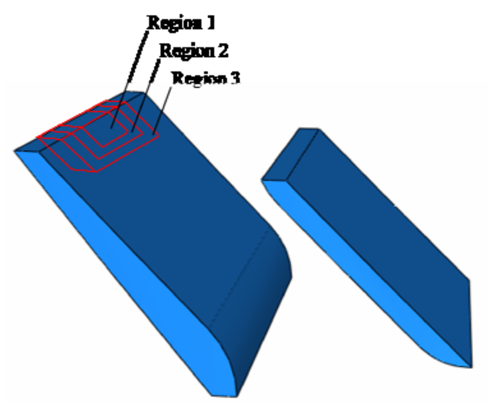

Fig. 3 Three regions assigned in the submodel

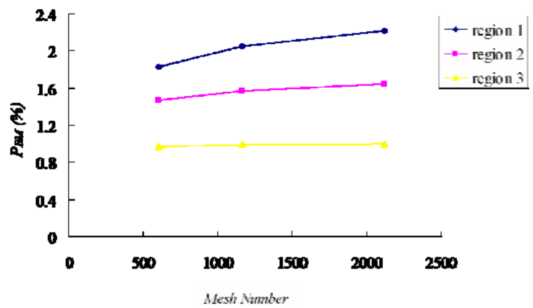

Fig. 4 Relationships between damage parameters and mesh numbers of three submodels based on Brown and Miller criterion

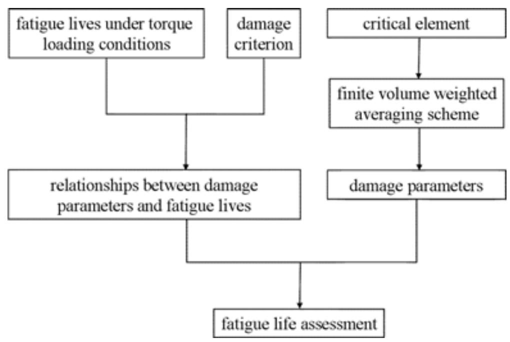

Fig. 5 A flow chart of the fatigue life assessment procedures

4. Results and Discussion

Relationships between damage parameters and fatigue lives based on Brown and Miller criterion, Socie et al. criterion, and Lohr and Ellison criterion are shown respectively in Figs. 6 (a), (b), and (c). Solid lines in these figures are basically obtained from the baseline measurements of a smooth cylinder subjected to the torque loading conditions versus various damage parameters in Yip and Jen [19]. Upper and lower bounds give two times and a half of the associated measured fatigue life based on the real line, respectively. A life-prediction model is usually considered to be suitable once the estimated fatigue life locates between the upper and lower bounds of the measurements. Fatigue life (upper bound, lower bound) of the hinge structure obtained via the averaged damage parameters of Brown and Miller criterion, Socie et al. criterion, and Lohr and Ellison criterion is then respectively 32284 (64568, 16142), 47366 (94732, 23683), and 26573 (53146, 13287) cycles.

Generally the degradation percentage of the torque cannot exceed 15% after 50000 loading cycles according to the specification requirements. It should be noted that in the experiments of Yip and Jen [19], the fatigue failure was identified as the load-carrying capacity of the structure reduced to a half of its initial value. Based on this viewpoint, all three damage criteria adopted here could provide too conservative fatigue life predictions. The possible reason that Socie et al. criterion gives the highest life could be the due to the contribution of the compressive normal mean arisen from the contact characteristics of the hinge structure. Nonetheless, Socie et al. criterion might predict rational life following conclusions of Liao et al. [17].

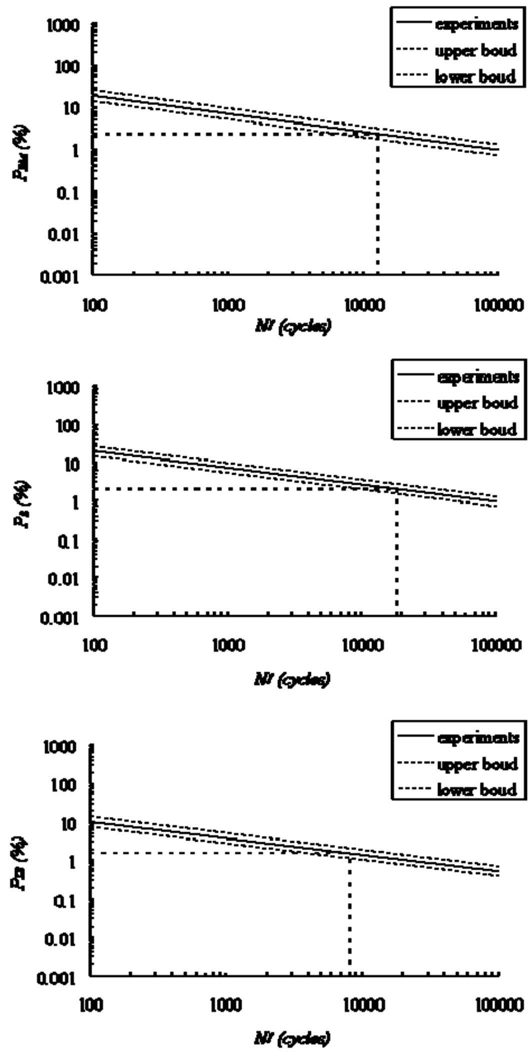

Fig. 6 Relationships between damage parameters and fatigue lives based on (a) Brown and Miller criterion, (b) Socie et al. criterion, and (c) Lohr and Ellison criterion

5. Conclusions

Several damage criteria based on the critical plane approach, the submodelling technique, and the finite volume weighted averaging scheme are used to assess the fatigue live of the innovative laptop hinge. The baseline measurements of the smooth cylinder subjected to the torque loading are adopted to construct relationships between damage parameters and fatigue lives. Simulations show that the Socie et al. damage criterion could give fair life predictions compared with the other two criteria.

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References

[1] X. Wei, K. Tim, Flexible hinges for piezoactuator displacement amplifiers: flexibility, accuracy and stress considerations, Precision Engineering, 19 (1996) 1-10
[2] T. Kosei, L. Yamato, Y. Takashi, Traction control of friction slider pair under a boundary lubrication condition, Surface and Coating,.100-101 (1998) 260-263
[3] Y. M. Huang, The stress analysis of hinge structure for notebook computer, Master Thesis, National Chung-Hsin University, Taiwan, 2001
[4] C. P. Kuo, Design of a new leaf type pivot in latchless portable computer, Master Thesis, National Chao-Tung University, Taiwan, 2004
[5] Y. C. Su, A study on wear behavior of hinge mechanism for notebook computer, Master Thesis, National Taiwan University of Science and Technology, Taiwan, 2005
[6] H. D. Hibbitt, B. I. Karlsson, E. P. Sorensen, ABAQUS user manual, Version 6.7, 2007
[7] J. Wang, Z. Qian, D. Zou, S. Liu, Creep behavior of a flip-chip package by both FEM modeling and real time moire interferometry, Trans. on ASME Journal of Electronic Packaging, 120 (1998) 179-185
[8] K. H. Teo, Reliability assessment of flip chip on board connection, IEEE/CMPT Electronics Packaging Technology Conference (1998) 269-273
[9] K.-C. Liao, H. H. Tsai, Reliability investigations of flip chip package with porous solder joints, The 4th International Conference on Thermal & Mechanical Simulation and Experiments in Micro-electronics and Micro-systems, Aix-en-Provence, France, March 30 – April 2 (2003) 63-67
[10] A.Fatemi, D. F. Socei, A critical plane approach to multiaxial fatigue damage including out-of-phase loading, Fatigue Fract. Engng. Mater. Struct., 11 (1988) 149-165
[11] D. F. Socie, Critical plane approaches for multiaxial fatigue damage assessment, Advances in Multiaxial Fatigue, ASTM STP 1191 (1993) 7-36
[12] C.-C. Chu, Fatigue damage calculation using the critical plane approach, J. Engineering Materials and Tech., 117 (1995) 41-49
[13] C. Ruiz, P. H. Boddington, K. C. Chen, An investigation of fatigue and fretting in a dovetail joint, Exp. Mech., 24 (1984) 208-217
[14] K. Iyer, G. T. Hahn, P. C. Bastias, C. A. Rubin, Analysis of fretting conditions in pinned connections, Wear, 181-183 (1995) 524-530
[15] M. Sralm, J. Flasker, I. Potrc, Numerical procedure for prediction the rolling contact fatigue crack initiation, I. J. Fatigue, 25 (2003) 585-595

[16] W. S. Sum, E. J. Williams, S. B. Lean, Finite element, critical-plane, fatigue life prediction of simple and complex contact configurations, International Journal of Fatigue, 27 (2005) 403-416
[17] K.-C. Liao, Y.-A. Cian, W.-C. Lin, Fatigue life assessment of an innovative laptop hinge, submitted to Materials and Design (2008)
[18] C.-C. Chu, F. A. Conel, J. J. F. Bonnen, Multiaxial stress-strain modeling and fatigue life prediction of SAE axle shafts, Advances in Multiaxial Fatigue, ASTM STP 1191 (1993) 37-54
[19] M.-C. Yip, Y.-M. Jen, Mean strain effect on crack initiation lives for notched specimens under biaxial nonproportional loading paths, J. Engineering Materials and Technology, 119 (1997) 104-112
[20] R. N. Smith, P. Watson, T. H. Topper, A stress strain function for the fatigue of metals, J. Materials, 5 (1970) 767-768
[21] M. W. Brown, K. J. Miller, A theory for fatigue failure under multiaxial stress-strain conditions, Proceedings Institution of Mechanical Engineers, 187 (1973) 745-755
[22] R. D.Lohr, E. G. Ellison, A simple theory for low cycle muliaxial fatigue, Fatigue of Engineering Materials and Structures, 3 (1980) 1-17
[23] D. F. Socie, T. W. Shield, Mean stress effects in biaxial fatigue of inconel 718, J. Engineering Materials and Technology, 106 (1984) 227-232
[24] D. F. Socie, L. A. Waill, D. F. Dittmer, Biaxial fatigue of inconel 718 Including mean stress effects, in : K.J. Miller, M.W. Brown (Eds.), Multiaxial Fatigue, Philadelphia, USA, 1985, pp. 463-481
[25] A. Fatemi, P. Kurath, Multiaxial fatigue life prediction under the influence of mean-stresses. J Basic Engng 110 (1988) 380-388
[26] C. F. Wang, Experimental analysis of low cycle fatigue life for cylindrical specimens with xircumferential grooves under out-of-phase multiaxial loading, Master Thesis, Chung-Hwa University, Taiwan, 2003
[27] C. L. Wei, Contact fatigue life analysis for pinned connection components by using finite element method, Master Thesis, Chung-Hwa University, Taiwan, 2005
[28] H. U. Akay, N. H. Paydar, A. Bilgic, Fatigue life predictions for thermally loaded solder joints using a volume-weighted averaging technique, ASME Transactions, Journal of Electronic Packaging 119 (1997) 228-234
[29] H. C. Cheng, K. N. Chiang, C. K. Chen, J. C. Lin, A study of factors affecting solder joint fatigue life of thermally enhanced ball grid array assemblies, Journal of the Chinese Institute of Engineers, 24 (2001) 439-451