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DIRECT CYCLIC METHOD FOR SOLDER JOINT RELIBAILITY ANALYSIS

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ABSTRACT

Low-cycle fatigue is a common failure mechanism in solder joints of a BGA in electronics packaging industry. Cyclic thermal loading leads to stress reversals and the accumulation of inelastic strain in the joints. In this paper the direct cyclic technique implemented in ABAQUS [1] has been used to predict the stabilized response of a BGA model subjected to cyclic thermal loading and cyclic bending loading respectively. The results are compared with the classical incremental simulation. Significant performance gains with very good accuracy of the direct cyclic approach are clearly demonstrated.

INTRODUCTION

In general, a structure subjected to cyclic thermal/mechanical loading will eventually lead to one of the following behaviors: (i) Elastic shakedown, for which there is no worry of low cycle fatigue; (ii) Plastic ratcheting, in which case the product/design is rejected; or (iii) Plastic shakedown with a stabilized state, in which the stress-strain relationship in each successive cycle is the same as in the previous one. Many studies have been performed in the past to investigate the reliability of solder joints under thermal fatigue loading [2-7]. In order to numerically predict the life of the solder joint, the traditional approach is to use the finite element simulation in which the cyclic loading is repetitively applied to the structure until a stabilized state is obtained. This approach is computationally expensive because it simulates the entire loading history until the stress-strain curve of the critical solder ball is saturated. The enclosed area of the stabilized stress-strain loop, i.e., the strain energy dissipated or the strain range in a stabilized deformation cycle is often used to predict the fatigue life of the solder joint. Coffin-Manson equation is often used for this purpose.

In this study, a direct cyclic method implemented in ABAQUS is applied to determine the asymptotic response of the critical solder joint under cyclic loading. The basis of this method is to construct a time-dependent displacement function that describes the structure response during one full loading cycle. A truncated Fourier series is then used to approximate the displacement function. The Fourier coefficients are solved by using a modified Newton method iteratively, and the updated displacement coefficients are then used in the next iteration. This process is repeated until convergence (stabilized solution) is achieved.

Considerable numerical expense, which is usually associated with the transient response, is avoided because the direct cyclic procedure seeks the stabilized state directly. Such approach was successfully used to predict fatigue life for a cylinder-head or exhaust manifold subjected to cyclic thermal/mechanical loadings in the power-train industry [8].

In this paper, two examples are presented for a flip-chip ball grid array (BGA) package subjected to thermal cycling and cyclic bending respectively. During thermal cycling, cyclic temperature fluctuates ranging from a minimum value of 233K to a maximum value of 358K. Under such operating conditions, plastic deformation and creep in solder joints is observed. The time-dependent material response is modeled with a viscoelastic-elastoplastic law. Temperature-dependent material properties are considered. For both cases, only one loading cycle is needed in the simulation to obtain the stabilized stress-strain response when direct cyclic approach is used. The classical incremental simulation is also carried out, and the results are compared with the direct cyclic analysis. The effectiveness of the direct cyclic approach (a CPU saving by a factor of 4) is clearly demonstrated.

DIRECT CYCLIC ALGORITHM

The algorithm to obtain a stabilized cycle is described in detail in the following references [1, 9, 10, and 11]. The basis of the direct cyclic method is to construct a displacement solution that describes the response of the structure at all times t in a load cycle with period T. We use a truncated Fourier series for this purpose,

$$u(t)=u_0+\sum_{k=1}^{n}\left(u_k^s\sin(2\pi k\frac{t}{T})+u_k^c\cos(2\pi k\frac{t}{T})\right)$$

where n represents number of Fourier terms, u_0, u_k^s and u_k^c are unknown displacement coefficients. We also expand the residual vector into a Fourier series in the same form as the displacement solution:

$$R(t)=R_0+\sum_{k=1}^{n}\left(R_k^s\sin(2\pi k\frac{t}{T})+R_k^c\cos(2\pi k\frac{t}{T})\right)$$

where each residual vector coefficient R_0, R_k^s and R_k^c corresponds to each displacement coefficient. The residual coefficients are obtained by tracking through the entire load cycle. At each instant in time in the cycle, ABAQUS obtains the residual vector, *R(t)*, by using standard element-by-element calculations, which, when integrated over the entire cycle, provides the Fourier coefficients for residual vector. Trapezoidal rule is used to integrate the residual coefficients. The residual coefficients at increment (i+1) are

$$R_0^{(i+1)}=R_0^{(i)}+\frac{\Delta t}{T}[R(t)+R(t+\Delta t)]$$

$$R_k^{s(i+1)}=R_k^{s(i)}+\frac{\Delta t}{T}[R(t+\Delta t)\sin(2\pi k\frac{t+\Delta t}{T})+R(t)\sin(2\pi k\frac{t}{T})]$$

$$R_k^{c(i+1)}=R_k^{c(i)}+\frac{\Delta t}{T}[R(t+\Delta t)\cos(2\pi k\frac{t+\Delta t}{T})+R(t)\cos(2\pi k\frac{t}{T})]$$

The displacement solution is obtained by solving for corrections to the displacement Fourier coefficients corresponding to each residual coefficient at the end of each iteration. The updated displacement solution is used in the next iteration to obtain the displacements at each instant in time. This process is repeated until convergence is obtained. Each pass through the complete load cycle can, therefore, be thought of as a single iteration of the solution to the nonlinear problem. Convergence is measured by ensuring that all entries of the residual coefficients are small.

The direct cyclic algorithm has been implemented into Abaqus/Standard after Version 6.4 [1].

NUMERICAL MODELS

A flip-chip BGA analyzed in this example is depicted in Fig 1. The second level solder ball (between the package and the PCB) is studied. The first level connection is simplified as one uniform layer of underfill. A full non-linear, quarter symmetry finite element model was created. In this paper, the eutectic solder 63Sn37Pb is applied. The BGA package is subjected to cyclic temperature loading ranging from 233K to 358K (Fig.2).Coupled plasticity-creep model in ABAQUS, which can be used for modeling the response of materials with significant time-dependent behavior as well as plasticity at elevated temperatures, is used to model solder. This material model consists of a plastic network followed with a viscous network in series. The Mises metal plasticity model with kinematic hardening is used in the plastic network, and the hyperbolic-sine law creep model with strain hardening is used in the viscous network. Since the elastic-viscoplastic response of solder varies greatly over this range of temperatures, temperature-dependent material properties are specified. The rest of the components are modeled with temperature-dependent elastic materials. All of the structural components are modeled with three-dimensional continuum elements in ABAQUS. The model consists of 23,500 second-order brick elements with reduced integration, resulting in a total of about 350,000 degrees of freedom for the case subjected to cyclic temperature loading. The mesh incompatibility at the refined bond package and BGA interfaces is handled with the "tied" constraint that is available in ABAQUS.

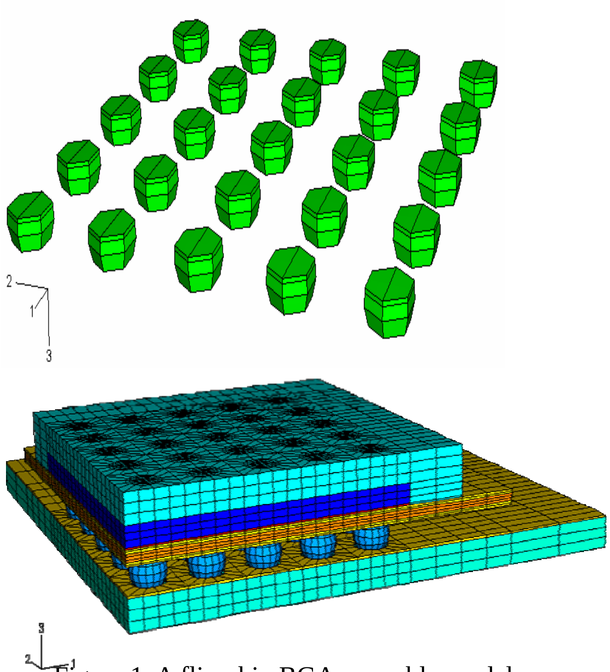

Figure 1. A flip-chip BGA assembly model.

The direct cyclic procedure with a fixed time increment of 75 and a load cycle period of 3600 is specified in this analysis, resulting in 48 increments for one iteration. The number of terms in the Fourier series and the maximum number of iterations are 31 and 100 respectively.

A similar but smaller model with 28,800 degrees of freedom is used for the case subjected to cyclic bending loading at room temperature. In this case, the direct cyclic procedure with a fixed time increment of 0.1 and a load cycle period of 4 is specified, resulting in 40 increments for one iteration. The number of terms in the Fourier series and the maximum number of iterations are 19 and 150 respectively.

For comparison purpose the same model is also analyzed using the classical transient analysis. Under cyclic temperature loading, it requires 8 repetitive steps before the solution is stabilized. For the case where it is subjected to cyclic bending loading, it requires 5 repetitive steps before the solution is stabilized.

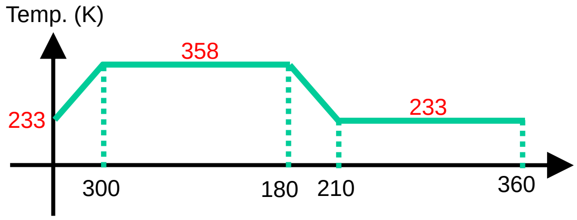

Figure 2. Temperature cycle.

RESULTS AND DISCUSSIONS

One of the considerations in the design of the BGA assembly is the stress distribution and deformation in the solder joint so that solder fatigue life can be predicted. It is found that maximum occurs in the "toe" area closest to the corner of the BGA assembly. Fig.3 shows the shear stress distributions obtained from the direct cyclic analysis and the classical approach. A comparison of the creep energy dissipation obtained in a direct cyclic analysis with that obtained in a transient approach is shown in Fig.4. A similar comparison of the inelastic energy dissipation obtained using both approaches is shown in Fig.5. A comparison of the evolution of the shear stress versus the inelastic strain obtained using both approaches is shown in Fig.6 for the case subjected to cyclic temperature loading. The shapes of the stress-strain curves and the amount of energy dissipated during the stabilized cycle are similar. So are the peaks and mean values of the shear stress over the stabilized cycle obtained using both approaches. The mean values of the inelastic strains over the stabilized cycle obtained using the approaches are somewhat different. One possible explanation is that when the stabilized cycle is not easily found (for example, when the loading is close to causing ratcheting), the state around which the stabilized solution is obtained may show considerably more/less "drift" than would be obtained in a transient analysis.

A similar comparison of the evolution of the stress versus the plastic strain obtained using both approaches is shown in Fig.7 for the case subjected to cyclic bending loading. The shapes of the stress-strain curves are again similar.

One advantage of using the direct cyclic method, in which the global stiffness matrix is inverted only once, instead of the classical approach in ABAQUS is the cost savings achieved. The saving will be more significant as the problem size increase since the stiffness matrix decomposition will be more expensive for larger problem. For the case subjected to cyclic temperature loading, it took approximately 80,832 CPU seconds to reach a stabilized state for a transient analysis as opposed to 16,833 CPU seconds for a direct cyclic analysis, leading to a factor 4.8 saving in CPU.

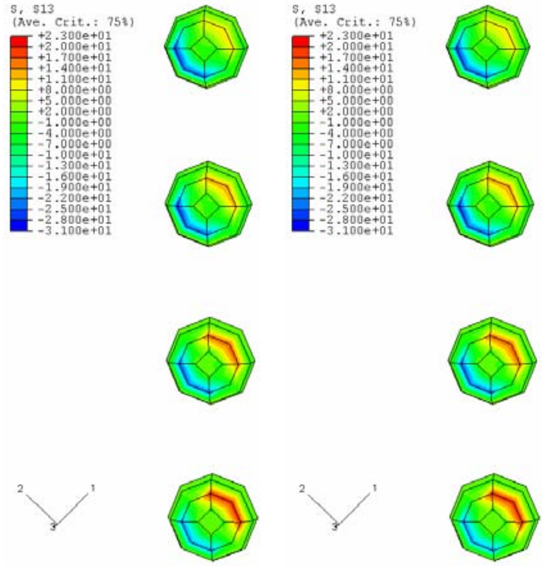

Figure 3. Shear stress distribution obtained using classical approach (left) and direct cyclic procedure (right).

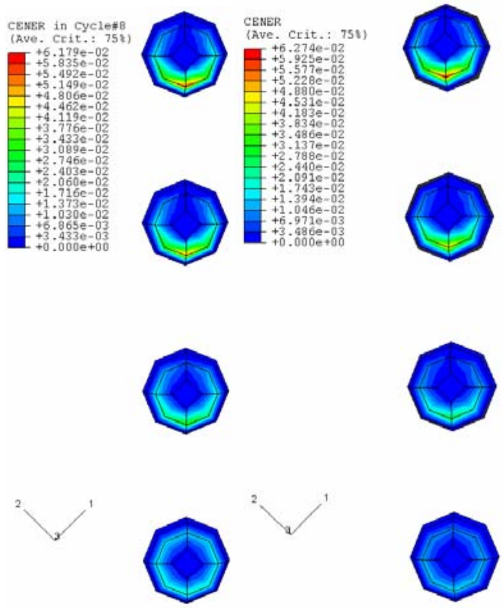

Figure 4. Creep energy dissipation obtained using classical approach (left) and direct cyclic procedure (right).

For the case subjected to cyclic bending loading, it took approximately 10,976 CPU seconds to reach a stabilized state for a transient analysis as opposed to 7,308 seconds for a direct cyclic analysis, leading to a factor 1.5 saving in CPU. The smaller CPU time saving for the case subjected to cyclic bending loading is expected since the model size is approximately 1/8 of the model used for cyclic temperature loading. In addition, as discussed earlier, one of the assumptions for direct cyclic analysis is that we use a global constant elastic stiffness matrix so that the equation system is inverted only once in order to achieve a computational efficiency. For a BGA model subjected to a relatively large bending stress in a relatively flexible structure, geometric nonlinearity becomes important. One of the approaches might be to update the geometry and initial stress stiffness after each iteration, or to take geometric nonlinearity fully into account during the stress/plastic strain recovery. However, none of these has been implemented in ABAQUS for direct cyclic as to date. Therefore, it is expected that the direct cyclic algorithm is likely to perform at a slow converged rate for this kind of flexible structure.

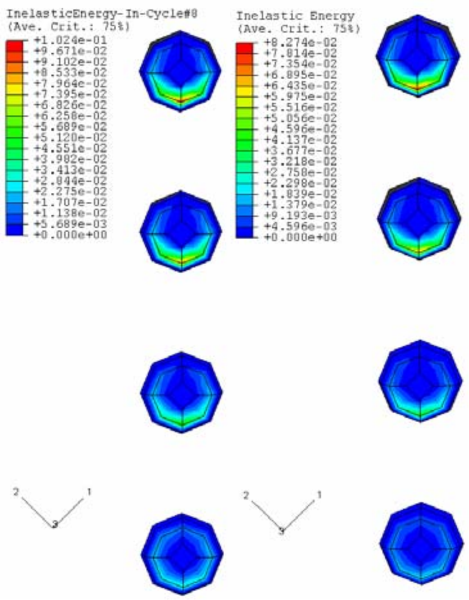

Figure 5. The sum of creep and plastic energy dissipation obtained using classical approach (left) and direct cyclic procedure (right).

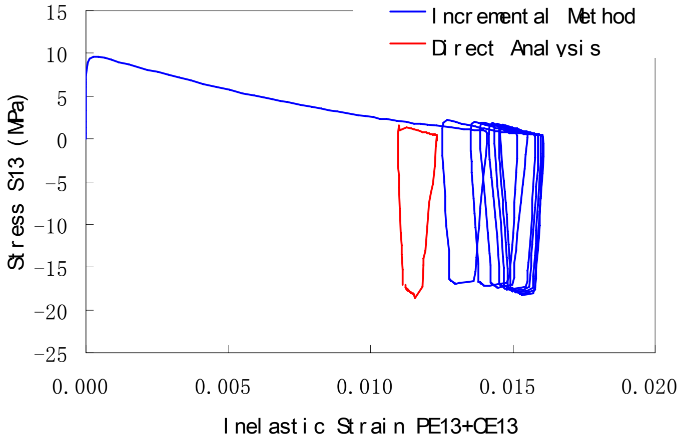

Figure 6. Comparison of the evolution of shear stress versus inelastic strain obtained using the direct cyclic analysis (red line) and transient analysis (blue line) approaches.

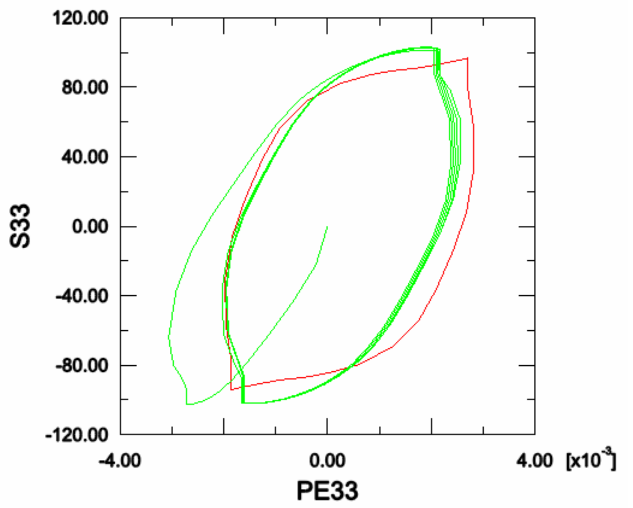

Figure 7. Comparison of the evolution of stress versus plastic strain obtained using the direct cyclic analysis (red line) and classic analysis (green line) approaches.

SUMMARY

The direct cyclic technique implemented in ABAQUS has bee used to predict the stabilized response of a BGA model subjected to cyclic thermal loading and cyclic bending loading respectively. The results are compared with the classical incremental simulation. Significant performance gains with very good accuracy of the direct cyclic approach are clearly demonstrated.

REFERENCES

1. ABAQUS User Manual, version 6.5, 2005.
2. Lau, J.H. Solder joint reliability: theory and applications, Van Nostrand Reinhold, New York, NY.
3. Dasgupta, A. et.al. “Solder creep fatigue analysis by an energy partitioning approach” Journal of electronic packaging, vol. 114, 1992, 152-60.
4. Engelmaier, W. “Fatigue life of leadless chip carrier solder joints during power cycling” IEEE Transactions on CHMT, Vol. 6 1983, 232-7.
5. Pao, Y.H. “A fracture mechanics approach to thermal fatigue life prediction of solder joints”, IEEE Transactions on CHMT, Vol.15, 1992, 559-70.
6, X. Fan, M. Pei and P Bhatti “Effect of finite element modeling techniques on solder joint fatigue life prediction of Flip-chip BGA packages, 56th Electronic components and Technology Conference (ECTC), San Diego, May30-June2, 2006.
7. S, Lee and X. Zhang “Sensitivity study on material properties for the fatigue life prediction of solder joints under cyclic thermal loading”, Circuit World, 24/3, 1998, 26-31.
8. T.M.L. Nguyen-Tajan, B. Pommier, H. Matournam, M. Houari, L. Verger, Z.Z. Du and M. Snyman “ Determination of the stabilized response of a structure undergoing cyclic

thermal-mechanical loads by a direct cyclic method” , ABAQUS user conference, 2003.

9. H. Maitournam, B. Pommier, J.J. Thomas, “Détermination de la réponse asymptotique d’une structure anélastique sous chargement thermomécanique cyclique”, C.R.Mécanique 330, pp. 703-708, 2002.

10. Q.S. Nguyen, “Stabilité et mécanique non linéaire”, Hermès Sciences, 2000.

11. B. Pommier, “Dimensionnement thermomécanique des culasses par la méthode cyclique directe”, Thèse de Doctorat de l’Ecole Polytechnique, 2003.