Advancing Solder Joint Modeling in PCBs: A Two-Scale Co-Simulation Approach for Shock & Vibration Analysis Using LS-Dyna

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1 Abstract

The integrity of solder joints in PCBs under dynamic loading conditions is critical for the reliability of electronic devices. Traditional modeling methods, such as representing solder joints with beam elements or solid elements in one-scale simulations, often face trade-offs between computational efficiency and accuracy. In this study, we introduce a two-scale co-simulation approach using LS-Dyna to address this challenge and provide both accuracy and efficiency in PCB analysis.

Conventionally, one-scale methods either sacrifice accuracy for computational speed by using beam elements or prioritize accuracy at the cost of computational efficiency through solid element modeling. However, our proposed two-scale approach strikes a balance between these two factors. By dividing the model into a global component representing the entire PCB assembly and a local component focusing solely on detailed solder joint modeling, computational resources can be optimized effectively.

A key advantage of the two-scale method lies in its two-way information exchange between the local and global models. Unlike traditional submodeling techniques, where information flow is typically one-way, our approach enables comprehensive communication between the global and local scales at each time step. This bidirectional exchange ensures that the effects of local solder joint behavior are accurately integrated into the global analysis, leading to improved accuracy compared to traditional one-scale methods.

To evaluate the effectiveness of the two-scale approach, we conducted a comparative analysis with one-scale simulations. Our results demonstrate that the two-scale method achieves superior accuracy, with an error rate of only 10% compared to the benchmark. Furthermore, the two-scale approach offers significant computational savings, reducing the running time by approximately 40% compared to one-scale methods. By accurately capturing the intricate dynamics of solder joints within the broader context of PCB assembly, our approach provides engineers with a reliable tool for optimizing the reliability and performance of electronic devices.

In summary, this study presents a novel two-scale co-simulation approach for shock and vibration analysis of PCBs, offering a balanced solution that combines accuracy and efficiency. By leveraging the advantages of both global and local modeling, our methodology represents a significant advancement in the field of PCB analysis.

Keywords: PCBs, Solder Joints, Shock and Vibration Analysis, Finite Element Analysis (FEA), Two-Scale Co-Simulation, Computational Efficiency

2 Introduction

Printed Circuit Boards (PCBs) have seen significant growth in recent years, largely due to their increasing integration into modern electronic devices. Their applications span a wide range of industries, including biomedical technology, where they are essential for devices like hearing aids and implants, as well as the aerospace sector, supporting heads-up displays. Additionally, PCBs are critical components in consumer electronics, such as smartphones, laptops, wearable devices like smartwatches, and play a crucial role in data center hardware.

Solders are a critical component of modern PCBs, serving not only to connect various elements such as resistors, capacitors, and chips but also to secure the multi-layered boards. Additionally, modern solder materials are often required to be lead-free in order to meet environmental regulations. However, lead-free solders are more prone to failure and are often regarded as the weakest point in a PCB [1].

One of the primary reliability concerns for electronic packaging is the impact of mechanical shock and vibration (S&V) on ball grid array (BGA) interconnects during shipping and handling. Finite element analysis (FEA) has been successfully applied to model these effects, with solder balls represented by solid elements [2,3]. The degree of freedom (DOF) of an FEA model depends on the number of solder balls and how they are modeled. In cases where the number of solder balls on a PCB is low [4], all can be modeled using a fine mesh. However, when the ball count is high, fine mesh is typically applied only to corner solder balls, with a coarser mesh used for interior ones [5]. For more complex systems, the global-local approach is often employed. This method utilizes a coarse mesh in the global model and a fine mesh in the local model to provide accurate stress calculations for the solder balls of interest [6].

Conventional approaches often use 1D beam elements to model solders, but even when combined with one-way sub-modelling, they fail to provide high-fidelity solutions (e.g., nonlinear behavior, failure modes). As a result, analyzing shock reliability and failure in solder joints, which involves both micro-scale joints and meso-scale chip packages, is a typical multi-scale problem. Recent advancements in multiscale modeling techniques have utilized a variety of bridging domain methods [7,8,9]. Notably, Wei et al. [10] introduced an innovative explicit-explicit (two-scale) domain decomposition approach to enhance the accuracy and efficiency of shock simulations for PCBs. This approach integrates the solder joint model with the macro-scale PCB through concurrent co-simulation, allowing for seamless scale bridging without intrusive modifications.

This paper presents a study on the development of an S&V modeling scheme aimed at reducing the modeling time of a complex printed circuit board assembly (PCB) system while maintaining high fidelity. A fully detailed model, where all relevant solder joints are represented with fine meshes (1-scale model), was used as a benchmark. We compared this with a simplified model using beam elements for the solder joints, and further, with a 2-scale model. In these comparisons, the PCB was modeled as a shell element. Additionally, we explored a case where the PCB was modeled as a solid element, with a detailed model of the local solder area, to assess both efficiency and accuracy. In the final example, only the solder joints of interest were modeled in detail, with a coarse mesh applied to the rest of the model. The efficiency and accuracy of the 1-scale and 2-scale models were compared across all cases.

3 Method & Model Setup

The fundamental concept of the two-scale simulation approach is that the variational dynamic equation of motion for an arbitrary displacement can be re-expressed in its weak form to determine both the macroscale and mesoscale displacement fields through integration by parts. The complete details of the co-simulation algorithm are available in the original work by Wei et al [10].

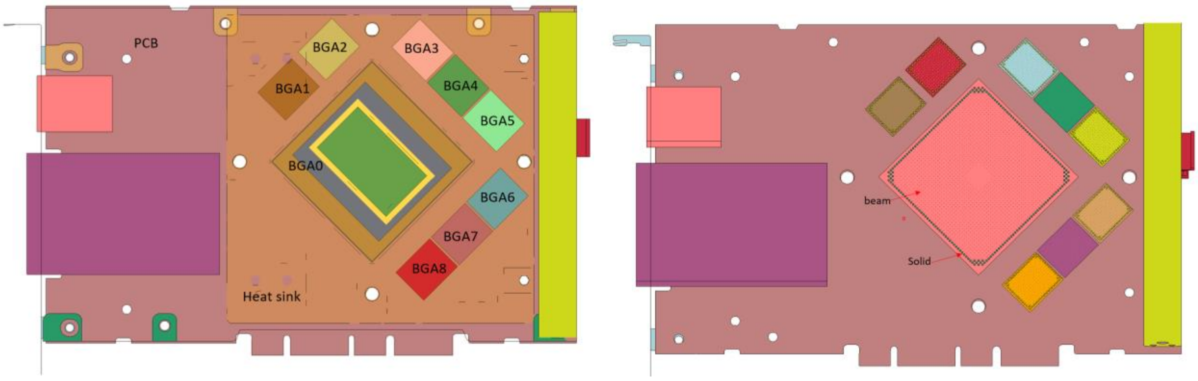


Fig.1: Shock analysis of a PCB with multiple BGA.

3.1 Modeling PCB utilizing Shell Element

All components are meshed using hexahedral elements [11]. In the first study, the PCB is modeled with shell elements, and comparisons are made among three cases: the benchmark one-scale model, the two-scale model, and the beam model. In the one-scale model, the solder joints are detailed with a fine mesh at the regions of interest located at the rim of each BGA, while the remaining solder joints are modeled using beam elements. The two-scale model is identical to the one-scale model, except that it separates the solder joints of interest into a local model. The beam model employs beam elements to represent all solder joints.

The boundary conditions applied to the model include the acceleration profiles shown in Fig. 2 and an initial vertical velocity of 6.85 m/s directed downward. Ansys LS-DYNA features several tied contact types, with the User's Manual, Volume I [12], offering guidance based on the specific elements being constrained.Body interactions are managed using CONTACT_AUTOMATIC_SURFACE_TO_SURFACE. Tied contacts are handled by *CONTACT_TIED_NODES_TO_SURFACE_OFFSET, CONTACT_TIED_SHELL_EDGE_TO_SOLID, and CONTACT_TIED_SURFACE_TO_SURFACE_OFFSET, accommodating the presence of shell, solid, and beam elements in the model. Additionally, global gravity is applied. The simulation duration is set to 6 ms.

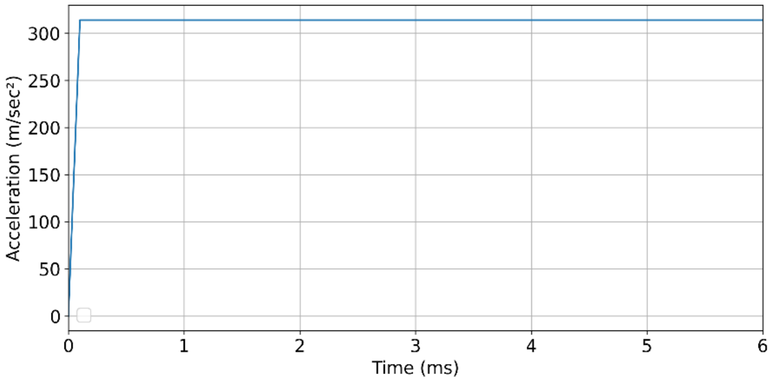


Fig.2: Acceleration profile applied at the tip of the PCB

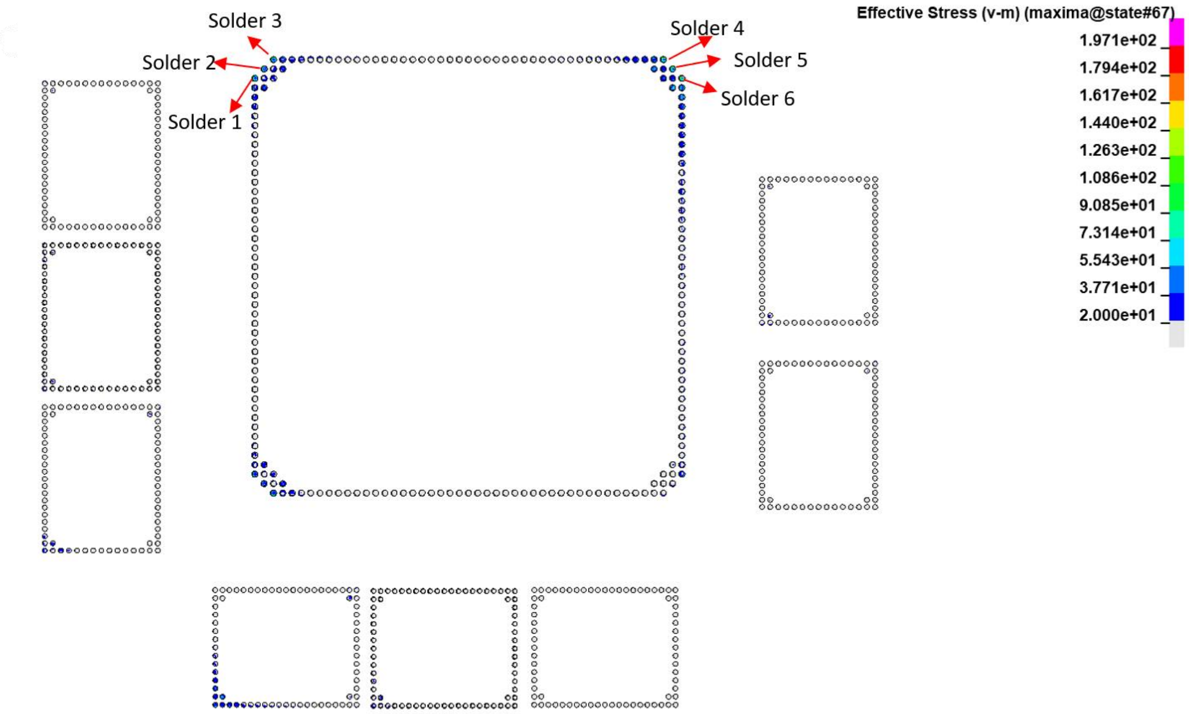


Fig.3: 6 Critical solder location

As anticipated, the solder balls with the highest risk are located at the corner of BGA0, as identified in Fig. 3, which illustrates the maximum effective stress over time in MPa. A comparison of the resultant displacements at these six locations is presented in Fig. 4. The results indicate that the beam model and two-scale model are nearly identical to the one-scale model, with negligible deviations. This demonstrates that both the two-scale method and the beam method can accurately capture the displacement field.

Regarding the sectional force, Fig. 5 presents the comparison results for the same six locations. The axial force of the beam element represents the sectional force in the beam method. Both the two-scale method and the beam method are capable of capturing the structural frequency and overall trend of the model. The results at all six locations reflect the same pattern. In general, the beam method underestimates the sectional force, whereas the two-scale method overestimates it by approximately 10% at the peak values. This overestimation offers a more conservative approach, which can be beneficial during the design phase.

As shown in Table 1, the beam method demonstrates significant advantages in terms of computational efficiency. With the use of 24 cores, the two-scale method reduces simulation time by 35% compared to the benchmark. The difference in time step size between the local and global models, which can vary by a factor of 10, further accelerates the simulation. Due to limitations in computational resources, only 24 cores were tested. However, it is anticipated that the efficiency of the two-scale method could be further improved with additional cores, allocated judiciously between the local and global models. An important advantage of the two-scale method is its ability to evaluate local stress at specific solder joints, a feature not accessible with the beam method.

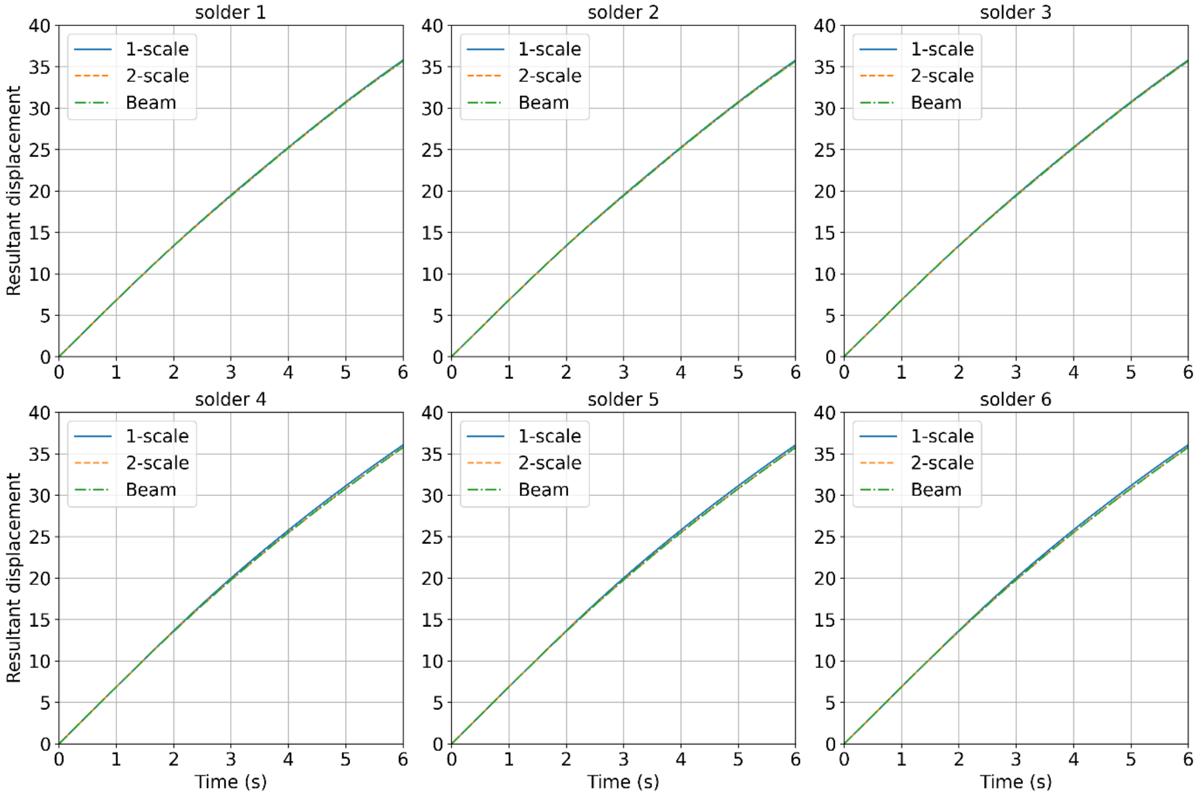
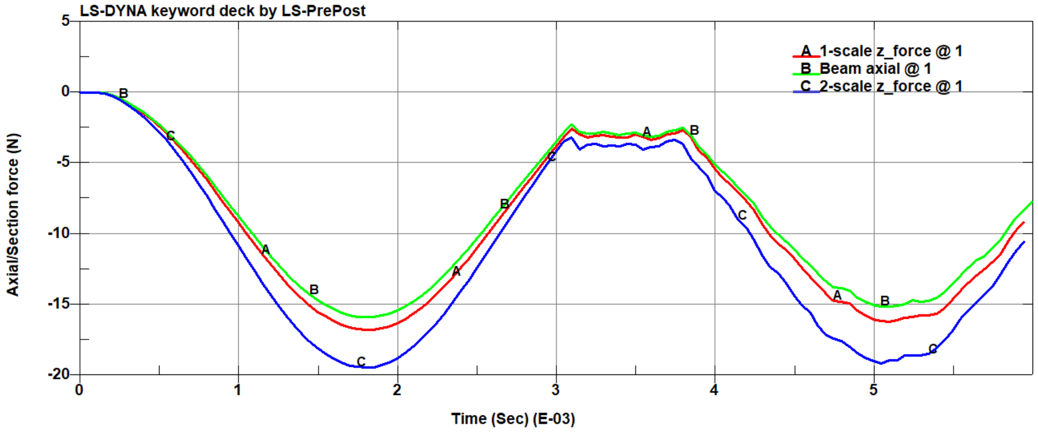


Fig.4: 6 Solder resultant displacement comparison at critical location


LS-DYNA keyword deck by LS-PrePost
Axial/Section force (N)
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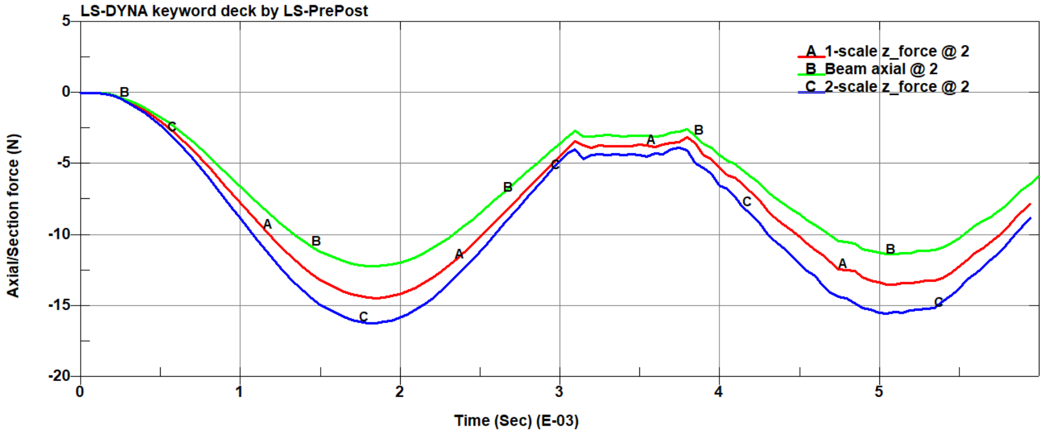
Time (Sec) (E-03)
A 1-scale z_force @ 1
B Beam axial @ 1
C 2-scale z_force @ 1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Time (Sec) (E-03)
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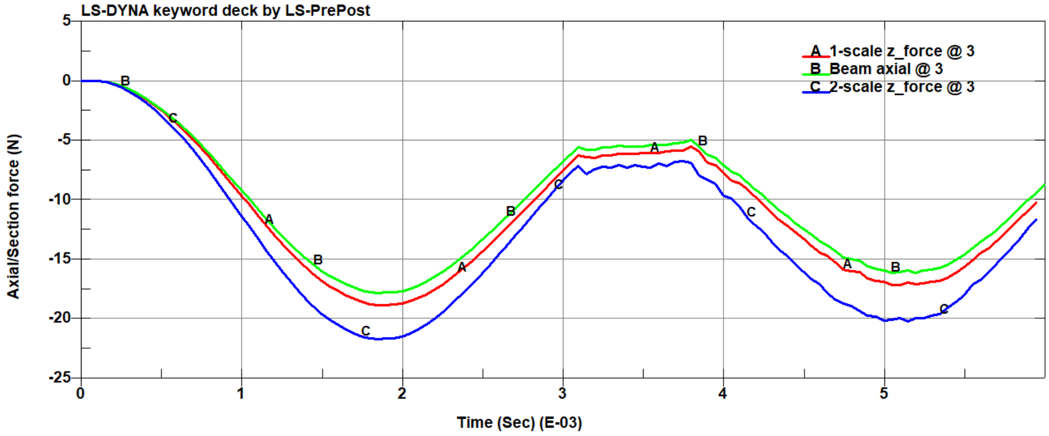
B Beam axial @ 2
C 2-scale z_force @ 2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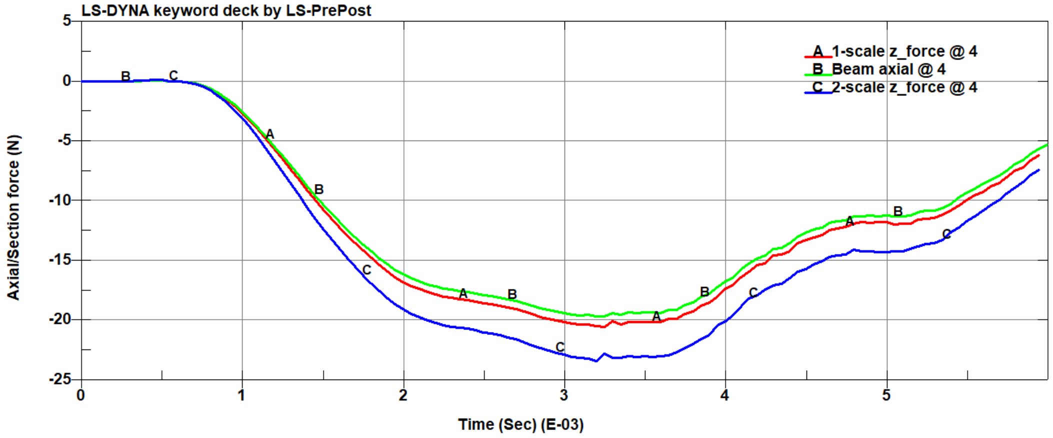
B Beam axial @ 3
C 2-scale z_force @ 3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B Beam axial @ 4
C 2-scale z_force @ 4

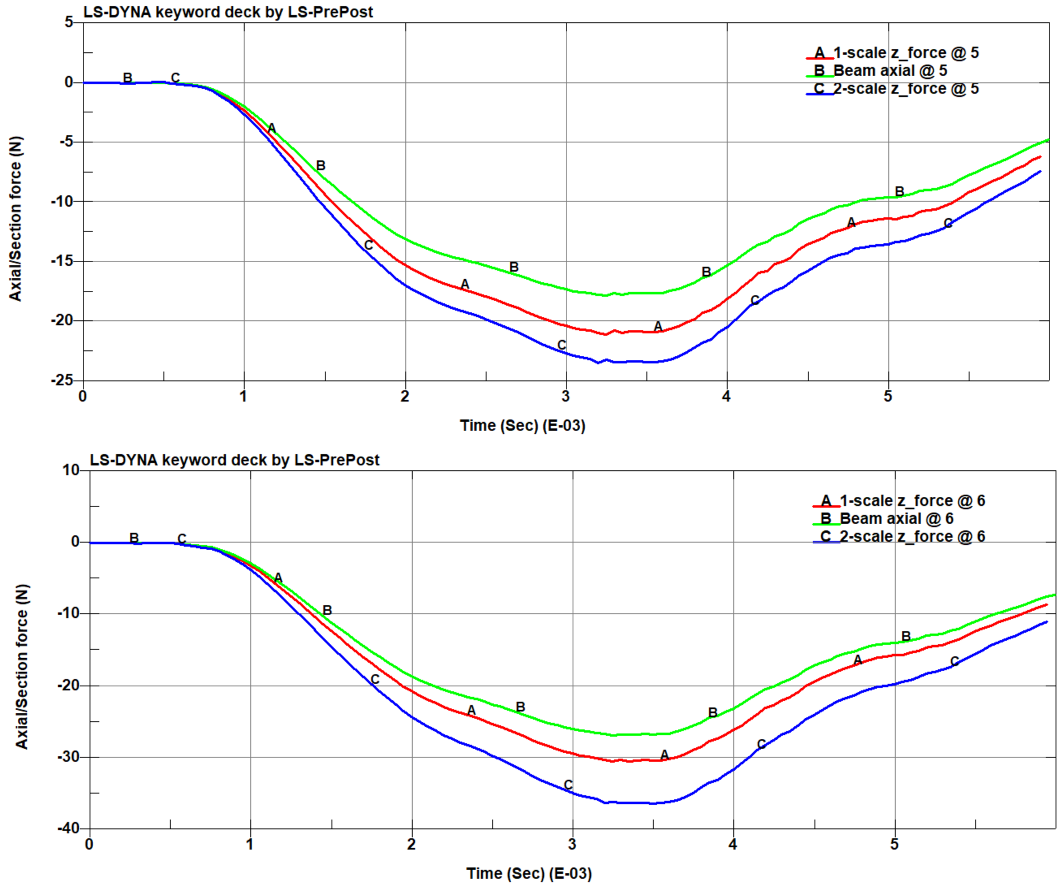

Fig.5: 6 Solder section force comparison at critical location

	Beam	One-scale	Two-scale
Number of cores	24	24	2 global, 22 local
Duration	6ms	6ms	6ms
Normalized calculation time	0.40%	100.00%	65.00%
Time step size	2.6E-08	3.87E-09	3.72e-9 (local), 2.62E-08 (global)

Table 1: Comparison of statistical results across three methods

3.2 Modeling PCB utilizing Solid Element

To obtain more accurate results, the following study models the PCB using four layers of solid elements. The remaining settings of the model are largely unchanged. A comparison will be made between the two-scale method and the one-scale method. Two scenarios are investigated: in the first, the cutting boundary is placed on the PCB, with the PCB and solder meshed at a similar, highly refined resolution. In the second scenario, the local model includes only the solder joints at the rim, which are the areas of interest.

3.2.1 Local model including a section of the PCB and solder

Regarding the resultant displacement, Fig. 6 presents the results at the corners of BGA 3, 5, and 8. The differences are negligible, as expected. In terms of the second-order result—effective stress—shown in Fig. 7, the two-scale model accurately captures the frequency and trend of the system, with approximately a 10% difference compared to the benchmark, which is consistent with previous studies. The efficiency of the two-scale method is highlighted in Table 2, showing a 36% reduction in simulation time compared to the benchmark. It is evident that the local model is significantly more computationally intensive than the global model. Thus, efficiency could be further improved by increasing computational power allocated to the local model or by reducing its size.

3.2.2 Local model including only solder joints of interest

As previously mentioned, a reduced-size local model was created, containing only the solder joints of interest located at the rims of BGA 3, 5, and 8 (shown in Fig. 7). The comparison of resultant displacement results presented in Fig. 6 indicates that the two-scale method performs well, matching the results of the one-scale method closely. Regarding effective stress, while the peak stress values are nearly identical, there is approximately a 10% difference in stress at the end of the analysis period. This discrepancy may be attributed to variations in mesh size between the local and global models, which requires further investigation in the future. In this scenario, we observed a significant increase in efficiency; by utilizing the two-scale method, we achieved a time savings of 73%, as shown in Table 3, while still obtaining high-fidelity results comparable to the one-scale method benchmark. These results instill confidence that the two-scale method is promising and can be applied to other applications.

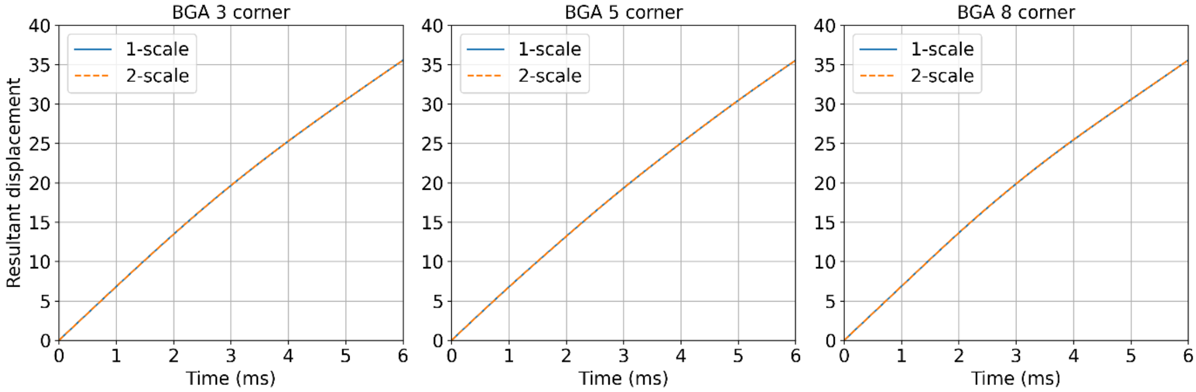

Fig.6: Comparison of solder resultant displacement at the corners of BGA 3, 5, and 8

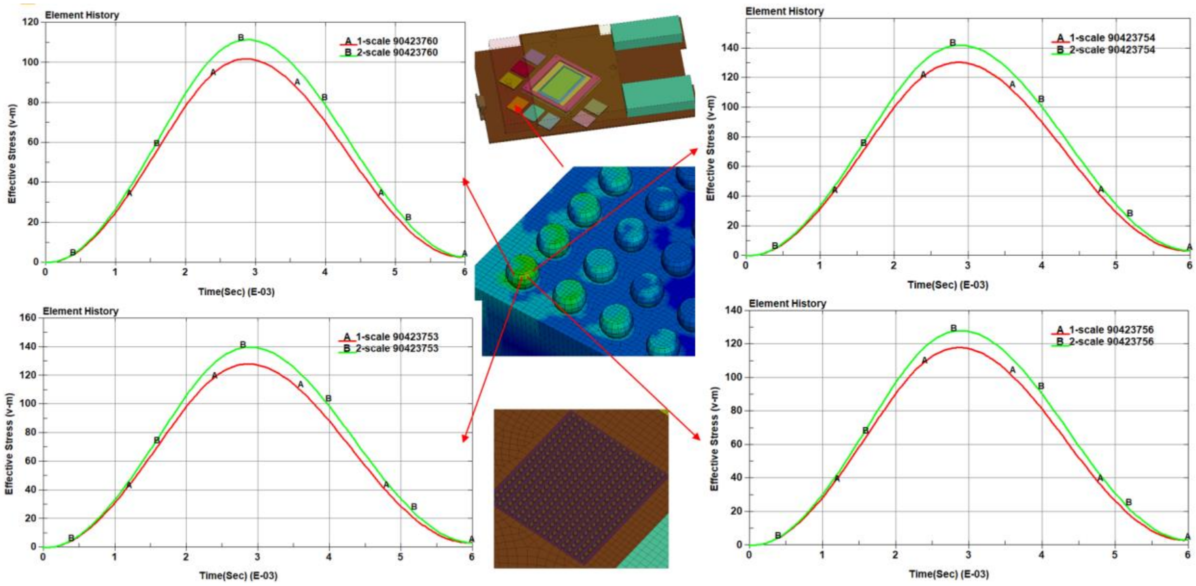

Fig.7: Solder effective stress comparison at critical location

	One-scale	Two-scale
Number of cores	80	2 global, 78 local
Duration	6ms	6ms
Normalized calculation time	100.00%	64.00%
Time step size	3.81E-09	3.79E-09 (local), 5.69E-08 (global)

Table 2: Comparison of statistical results between two methods

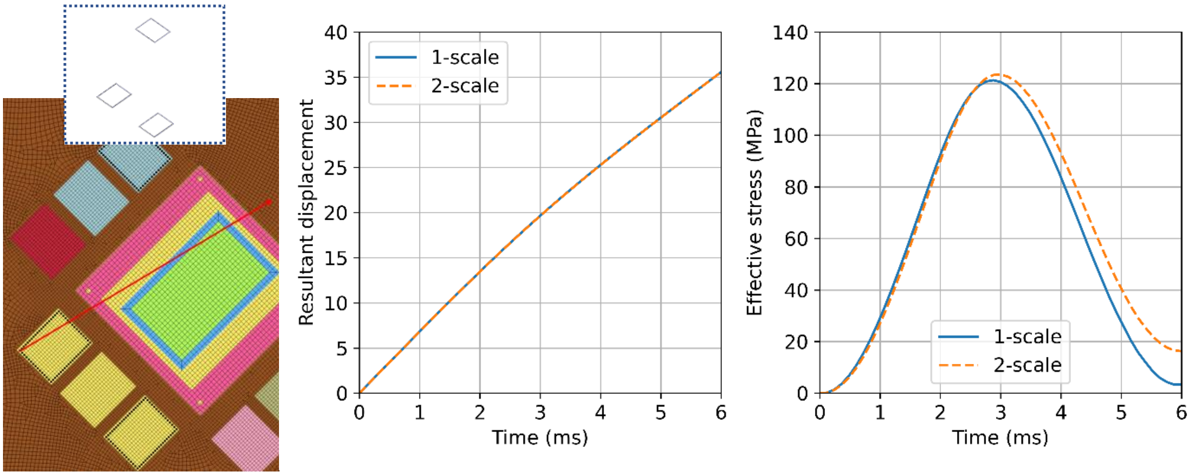

Fig.8: Local model of solder joints with displacement and effective stress results

	One-scale	Two-scale
Number of cores	28	15 global, 13 local
Duration	6ms	6ms
Normalized calculation time	100.00%	27.00%
Time step size	1.20E-08	1.08E-8 (local), 4.27E-08 (global)

Table 3: Comparison of statistical results between two methods

4 Summary

This paper presents a study on the shock analysis of a printed circuit board (PCB) employing the latest state-of-the-art two-scale method. Compared to the traditional approach of modeling ball grid arrays (BGAs) with beam elements, the two-scale method demonstrates its validity and effectiveness. The one-scale model serves as the benchmark, providing accurate results while requiring considerable computational resources. By modeling both the solder joints and the corresponding PCB sections within the local model, the two-scale method achieves high-fidelity results along with reasonable efficiency improvements. When the local model is confined to the solder joints of interest, we observe a substantial increase in efficiency—specifically, a 73% improvement—without compromising an acceptable level of accuracy. Overall, the findings suggest that the two-scale method is a promising approach that effectively balances accuracy and computational efficiency, making it suitable not only for PCB shock analysis but also for a wide range of other applications.

5 Literature

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