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An Accuracy and Efficiency Study on the Use of Symmetrical Numerical Models of Electronic Packages under Various Loading Conditions

Mohammad A. Gharaibeh*

Department of Mechanical Engineering, Faculty of Engineering, The Hashemite University - Zarqa, 13133, Jordan

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Abstract

This paper investigates the accuracy, validity, and the efficiency of the use of symmetry-based finite element models in simulating the mechanical behavior of board-level electronic assemblies under various loading conditions. In this investigation, ANSYS software was adopted to build the quarter-symmetry of the full geometric models, and to conduct the analysis. Various analysis types, including static, modal, harmonic, transient and spectrum analysis were considered. The results of the symmetric model were extensively compared to those of the full model in each analysis type. Based on this comprehensive comparison, it is recommended to use the symmetrical numerical models in static, transient and spectrum analysis types. However, the use of such models is not generally encouraged in eigenvalue problems like modal analysis. For harmonic analysis, a cautious use of the symmetry models, combined with full solution methods, is encouraged. Additionally, a data on the computational cost, such as solution time and memory usage, of the use of symmetric models was reported. Finally, the computational efficiency results showed high preference in using quarter symmetry models over full models..

Keywords: Finite Element Modeling, Symmetric models, electronic packages, computational efficiency.

1. Introduction

Board-level electronic packages analysis is of great interest over the world [1, 2]. In real-life, electronic products are subjected to various static as well as dynamic loading conditions [3]. Over the years, finite element method (FEM) has been proven to be effective in the analysis and characterization of board-level electronic assemblies [4, 5]. One major hand-waving concern in building accurate and efficient finite element analysis (FEA) models of electronic systems is the computational cost and solution time due to the wide range complexity of the electronic structure [6]. To overcome this issue, researchers have constantly adopted, wherever possible, the use of symmetrical FEA models. For example, Pitarresi et al. [7] considered half-symmetry FE models in the analysis of board-level electronic packages under drop impact. Luan et al. [8] used quarter-symmetry models in the investigations of thin-profile fine-pitch ball grid array (TFBGA) and quad flat no-lead (QFN) packages in impact loadings as well. Many other researchers have adopted symmetrical computational models of board-level electronic vehicles in drop and shock loading condition [9-14]. For static bending, Zhang et al. [15] considered quarter symmetry in the analysis of pad cratering failures of plastic ball grid array (PBGA) systems. Baber and Guven [16] applied half-symmetry, quarter-symmetry and one-eighth-symmetry FE models in their reliability and fatigue life assessment of electronics under static bending and thermal cycling tests. Farley et al. [17] employed half-symmetry simulations in the investigations of the fatigue characteristics of copper traces in packages subjected to cyclic bending. In addition to drop and bending tests, symmetrical models have been widely used in the analysis of board-level electronic packages under thermal cycling [18-21], harmonic and random vibrations [22-26] and combined temperature-vibration loading conditions [27, 28].

Although the symmetry FE models have been widely considered, other researchers analyzed full models. The definition of full models mean that no symmetry was incorporated, and the full geometry of electronic board was modeled and hence analyzed. Xia et al. [29-31], Tang et al. [32], Gharaibeh [33-36] and Gharaibeh et al. [37-41] have used such full models in the fatigue life and reliability evaluations of board-level electronic assemblies under harmonic as well as random vibration excitations. Full models were also adopted in the study for electronics under drop/impact [42, 43], static bending [44] and combined loading conditions [44-49].

In addition to the assessment of the failure of electronic packages, full finite element models were applied the studies that obtain the in-plane material properties (modulus of elasticity, shear modulus and Poisson's ratio) of printed circuit boards (PCB) using finite element model

* Corresponding author e-mail: mohammada_fa@hu.edu.jo.

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updating techniques [50-52]. Such studies include the execution of modal analysis to obtain the natural frequencies and mode shapes of the electronic structures. The use of full and symmetrical models is continuously seen in other engineering applications [53-58].

As it is seen from the previous literature survey, both symmetry-based and full computational models were used in various kinds of analysis. However, there is a lack of understanding about when and how to use full or symmetry models to achieve computationally effective models, in terms of computer memory usage and solution time, without affecting accuracy. For this reason, the aim of the current paper is to provide extensive finite element study on the accuracy and efficiency of the use of both full and symmetrical models of board-level electronic packages under various conditions including static, modal, harmonic, transient and spectrum analysis-type problems.

We start by introducing the details of the test vehicle considered in this study followed by the finite element modeling details and a brief introduction on all the analysis types tested throughout the analysis. The comparison results between full and symmetry-based models are presented subsequently. Finally, this paper summarized the findings and provided recommendations on the use of full and/or symmetry models in the suitable analysis type and loading condition.

2. Description of the Problem

As mentioned earlier, this work aims to test the accuracy, validity and efficiency of the use of symmetrical finite element models of board-level electronic packages subjected to various loading conditions. Consequently, the loading conditions considered in this paper include, static loading, impact loading, random as well as harmonic vibration loadings and natural frequency and mode shape analysis. In summary, static, dynamic and eigenvalue problems were considered.

The board-level configuration evaluated in this work appears in Figure 1. This configuration is assembled from a squared printed circuit board (PCB) with $76 \times 76\ mm^2$ in-plane dimensions and a $1\ mm$ thickness, an Amkor CABGA 256 Integrated Circuit (IC) component of 16×16 full area array SAC305 solder interconnects. This highly symmetric squared configuration was purposefully chosen to create a quarter-symmetric and full finite element models, as will be described in the following section.

3. Finite Element Modeling

In this paper, ANSYS commercial software Release 19.0, installed on a personal computer (PC) with an Intel ® Core ™ i7-4790 central processing unit (CPU) at 3.60 GHz processer and 8 Gigabytes of RAM, was adopted to create the FE models and to execute all the analysis types considered in the present work.

In the analysis, two types of FE models were investigated: Full model and Quarter-Symmetry (QS) model. In the full model, shown in Figure 2(a), the previously described test sample was modeled with full geometric properties. In contradiction, the QS model only one quarter was modeled, Figure 2(b), per the geometric symmetry of the tested configuration. In both full and QS models, only linear elastic material properties were used for all parts of the electronic assembly. The purpose of selecting elastic material behavior is directed towards the validity and efficiency of the use of symmetric computational models in various types of analysis as it does not provide or report any reliability or fatigue data. Material Properties used in the present study are listed in Table 1.

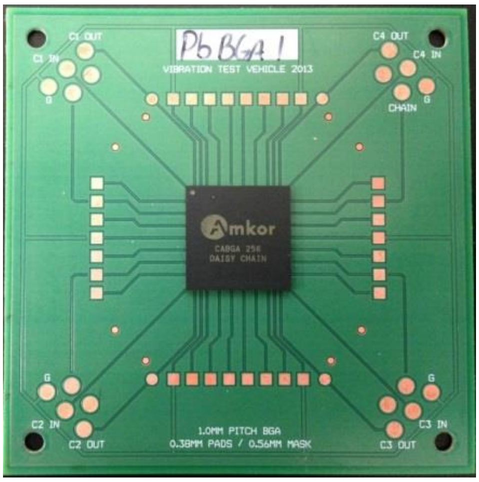
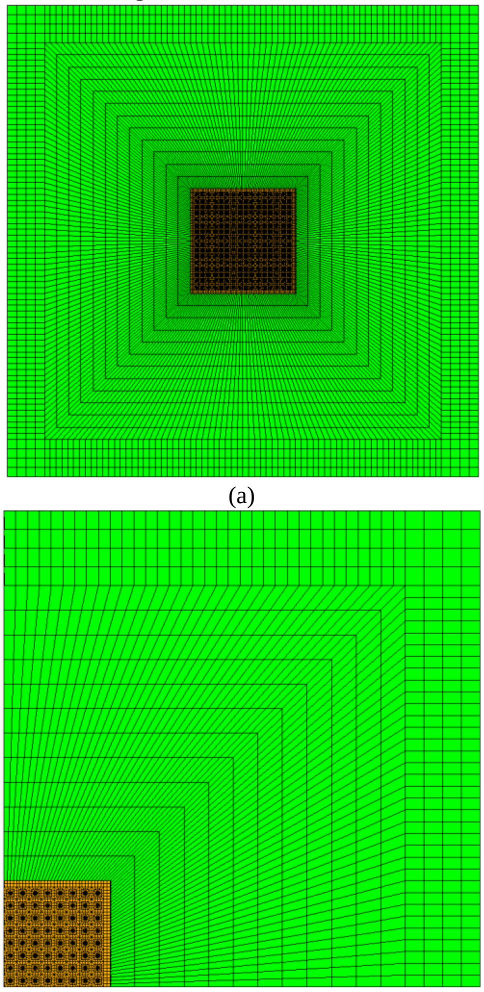


Figure 1. Test Board Details.



(a)

(b)

Figure 2. Finite element models (a) full model (b) quarter symmetry model.

Table 1. Linear elastic material properties used in the FE model.

Material Parameter	PCB	Component	Solder joints SAC305	Copper pads
Young's Modulus (GPa)	32.0	27.0	43.0	120.0
Poisson's ratio	0.24	0.25	0.36	0.30
Density (kg/m^3)	3000	1100	7400	8800

For mesh properties, SOLID 185 ANSYS element with full integration properties was used in both full and QS models. Additionally, care was taken to generate the same mesh characteristics, i.e., element size and distribution, and to eliminate the effect of mesh discrepancies in QS and full model and in each model as well. In the full model, 178,880 elements and 220,294 nodes were generated while the symmetric model contained 44,270 elements and 55,330 nodes.

For the boundary conditions, the full model was constrained in all directions at each corner of the PCB. The QS model was restrained at the top-right corner of the PCB in all directions and the symmetry boundary conditions were applied on the planes of symmetry.

The analysis types simulated in the current investigation included static, modal, harmonic, transient and spectrum analysis. For analysis robustness, ANSYS Sparse Solver was adopted to solve for the full and symmetry models in all analysis types considered.

In static analysis, a self-weight of $1g$ was applied, where g is the acceleration of gravity and $g = 9.81\ m/s^2$. Although it is straightforward and well-known that in static problems both QS and full models are expected to produce the same results, it was reported here for completeness.

In modal analysis, the first ten natural frequencies and mode shapes of the symmetry-based and the full model were calculated. Mathematically, modal analysis is an eigenvalue value problem in which the natural frequencies are the eigenvalues, and the mode shapes are the eigenvectors. Although, it does not provide any strain or stress data, but it provides important dynamic characteristics of the tested structure and it is widely used in the process of evaluating the in-plane material properties of the PCBs and other electronic structure.

Harmonic analysis was also incorporated in the present study to ensure the validity of the use of the symmetric FEA models in dynamic problems with steady-state response. In ANSYS, two harmonic analysis methods are available: Full method and Mode superposition method [57]. The full method is the most straightforward solution method for conducting a harmonic analysis as it uses the full system matrices without matrix reduction to compute the harmonic response, i.e., displacements, in a single pass. However, it is computationally expensive. The second method, the mode superposition (MSUP) method, is faster and less computationally intensive as it sums the factored eigenvectors (mode shapes) of a previously conducted modal analysis to compute the harmonic response. However, to calculate stresses and strains of the analyzed structure, it requires a second solution step; the expansion pass step, The MSUP method accuracy, which highly depends on the number of the mode shapes incorporated in the solution, the higher the better.

In the present work, harmonic analysis was adopted to simulate the base excitation vibration problem of the test piece. A base input acceleration of $1g$ was applied on the fixed locations, i.e., PCB 4 corners in the full models and the top-right corner in the QS model. The damping ratio used in this analysis is 0.5%, as extracted from a previous study of the author [33]. For completeness, both solution methods, full and MSUP, were simulated. In MSUP, two cases were tested. The first case (MSUP 05), only five model shapes were incorporated in the simulation and the second case (MSUP 15), fifteen modes were included in the solution.

Another important analysis type tested in this investigation is transient analysis. This type of analysis is commonly used to solve for dynamic problems with transient response. As in harmonic analysis, two solution methods are available in conducting a transient analysis in ANSYS: full and mode superposition (MSUP) method [57]. The properties, advantages, and disadvantages of each solution method here are the same of those discussed in harmonic analysis. In electronic packages research, transient analysis is widely used for simulating drop tests. In the present study, the shock profile of JEDEC B-condition [58] with a standard half-sine wave base acceleration of $1500g$ input level and pulse duration of $0.5\ msec$ was considered. The load application procedure and damping ratio use in transient analysis are similar to those of the previously discussed harmonic analysis. Additionally, full and mode superposition with MSUP 05 and MSUP 15 methods were studied in this type of analysis.

The last analysis type performed in this study is spectrum analysis. ANSYS spectrum analysis is commonly used to simulate base excitation random vibrations problems. In ANSYS, random vibration problem with spectrum analysis is also called power spectral density (PSD) analysis [53]. Mathematically, PSD is a statistical measure that is defined as the root-mean-square (RMS) value of a given random variable. In random vibration simulations, it is always assumed that the dynamic input loading has a zero mean, and it follows the properties of Gaussian or normal distributions. During the solution process of a PSD analysis, it requires a combination of the mode shapes, which are to be obtained from modal analysis. More mode combinations lead to more accurate results, similar to MSUP method in harmonic and transient analyses. In the present work, a base acceleration with a PSD input level of $1\ g^2/Hz$ with a damping ratio of 0.5% was applied at the fixed locations, as previously presented in harmonic and transient analysis. In the mode combination step, two cases were simulated MSUP 05 and MSUP 15 to combine five and fifteen mode shapes during the analysis, respectively.

4. Results and Discussions

4.1. Static Analysis

As mentioned earlier, it is straightforward and well-known that the results of the static solution in full and symmetric models are expected to be in exact match.

However, this paper comes to document all of that along with other analysis types for completeness. The results of static analysis are depicted in Figure 3 and Figue 4. Figure 3 presents a contour plot for the out-of-plane displacements from both QS and full models and Figue 4 shows the von Mises stress of the solder joints area array. Apparently, displacement and stress results from both model types are the same as expected, which further validates the efficiency and accuracy of the use symmetry-based numerical models in such kind of problems.

4.2. Modal Analysis

Modal analysis results, i.e., natural frequencies and mode shapes, from both model configurations are included in Table 1 and Table 2. From Table 1, it is clearly observed that natural frequencies in the full and QS models, i.e., eigenvalues, do not match, except for the first mode. Same observations can be noted in Table 3. It can be explained that not all mode shapes are symmetric and that most of the eigenvectors are antisymmetric (axisymmetric). By taking a deeper look into the results, it could be seen that the natural frequencies and operating deflection shapes of the fourth and sixth modes of the full model are matching the second and third modes of the symmetry-based model, respectively. This is because that these two specific modes are symmetric. While all other shown mode shapes are antisymmetric, they differ in the QS model and the full model.

Here, it can be concluded that the symmetry-based computational models cannot be used in the analysis of eigenvalue problems like modal analysis as well as buckling analysis.

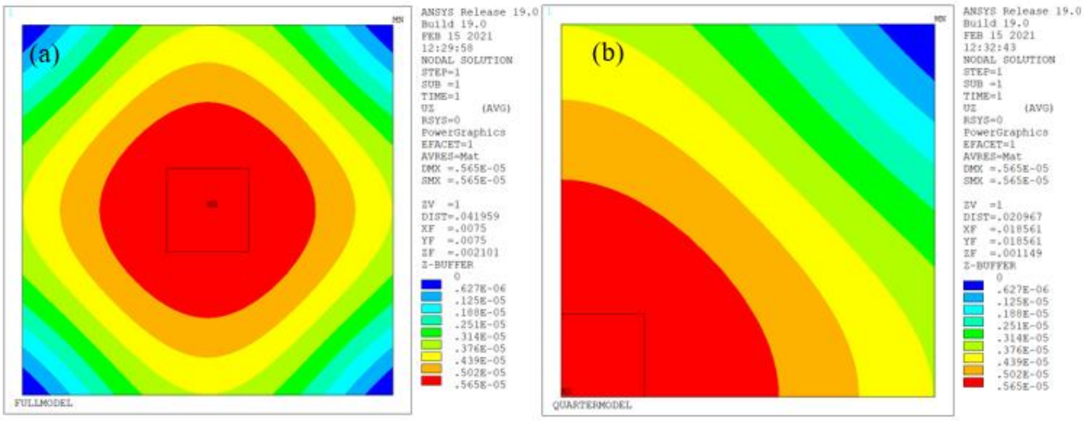
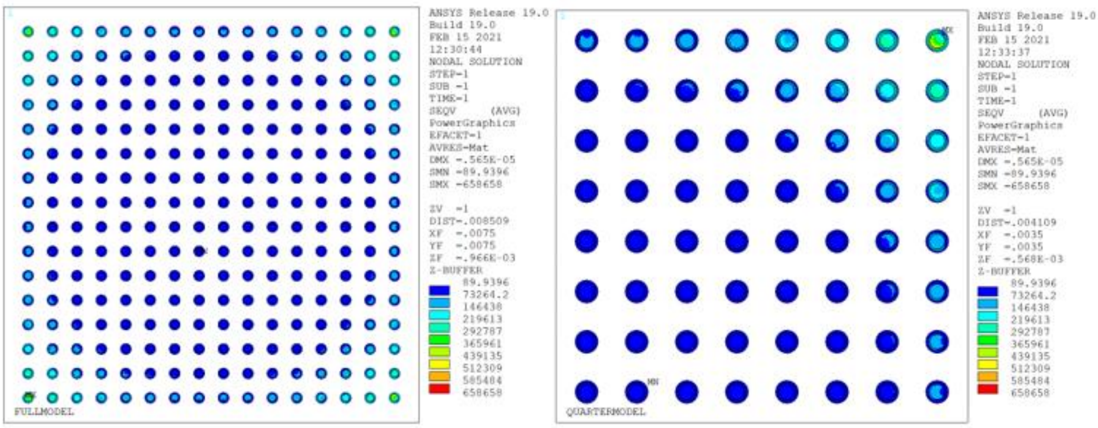


Figure 3. Contour plots for the out-of-plane deflections using (a) full and (b) QS models.



(a) (b)

Figure 4. Contour plots for the solder area array von Mises stresses using (a) full and (b) QS models.

Table 2. Natural frequency comparison between full and QS models.

Mode #	Full model natural frequency [Hz]	QS model natural frequency [Hz]
1	235.85	235.85
2	502.97	712.98
3	502.97	1283.5
4	712.98	2622.0
5	1213.7	3509.1
6	1283.5	4035.7
7	1497.0	4623.9
8	1497.0	6479.3
9	2056.1	7883.8
10	2221.6	8374.2

4.3. Harmonic Analysis

As stated previously, harmonic analysis was performed to simulate the base excitation with harmonic input problem on both QS and full model systems. Three cases, including full, MSUP 05 and MSUP 15, were considered. Figure 5shows the out-of-plane displacements at the board center frequency functions for all simulated cases in frequency range from 1 Hz to 15 KHz. As shown in Figure 5(a), the board transverse deflections from both QS and full models, using full solution methods, are exactly the same and right on top of each other. This concludes that the use of symmetry based FEA models is totally valid and accurate. For Figure 5(b) and Figure 5(c), the PCB deflections are not the same from the full and the QS model. Specifically, for MSUP 05 solution method (Figure 5(b)). For MSUP 15 (Figure 5(c)), the board deflections are in better match with the full solution methods as more mode shape, i.e., eigenvectors, were invoked in the solution. As a result, while using symmetric models in harmonic analysis with mode superposition, care must be taken, and sufficient number of mode shapes has to be included in the solution. For safe use of symmetry-based models in harmonic analysis, the use of the full solution method is highly encouraged for best accuracy. For a closer look, Figure 6shows the board deformations for all solution methods as extracted from full and QS models, respectively. For Figure 6(a), it is obviously seen that the data of MSUP 15 matches the results of the full solution method while MSUP 05 misses the resonant peaks for excitation frequencies exceeding 3 KHz. This is due to the fact that MSUP 15 uses 15 modes in the solution while MSUP 05 uses only 5 modes. Such findings lead to the statement that even when using full numerical models, careful selection of the number of modes to be incorporating the mode superposition method is strictly essential. If this is not easily obtained, the use of full solution method is strongly recommended. Figure 6(b) depicts the deflections all solution methods as extracted from the symmetry based FEA model. This shows that the use of full solution method, even in symmetric models, provides accurate and valid results compared to full models. However, the use of MSUP methods is not encouraged as important details will be missed which leads to erroneous results.

In summary, the use of symmetry-based models in harmonic analysis is valid and efficient only if full solution method is performed. Otherwise, erroneous and maybe disastrous results might be achieved. Additionally, if mode superposition solution methods were used, in both full and symmetric models, the inclusion of sufficient number of mode shapes is required.

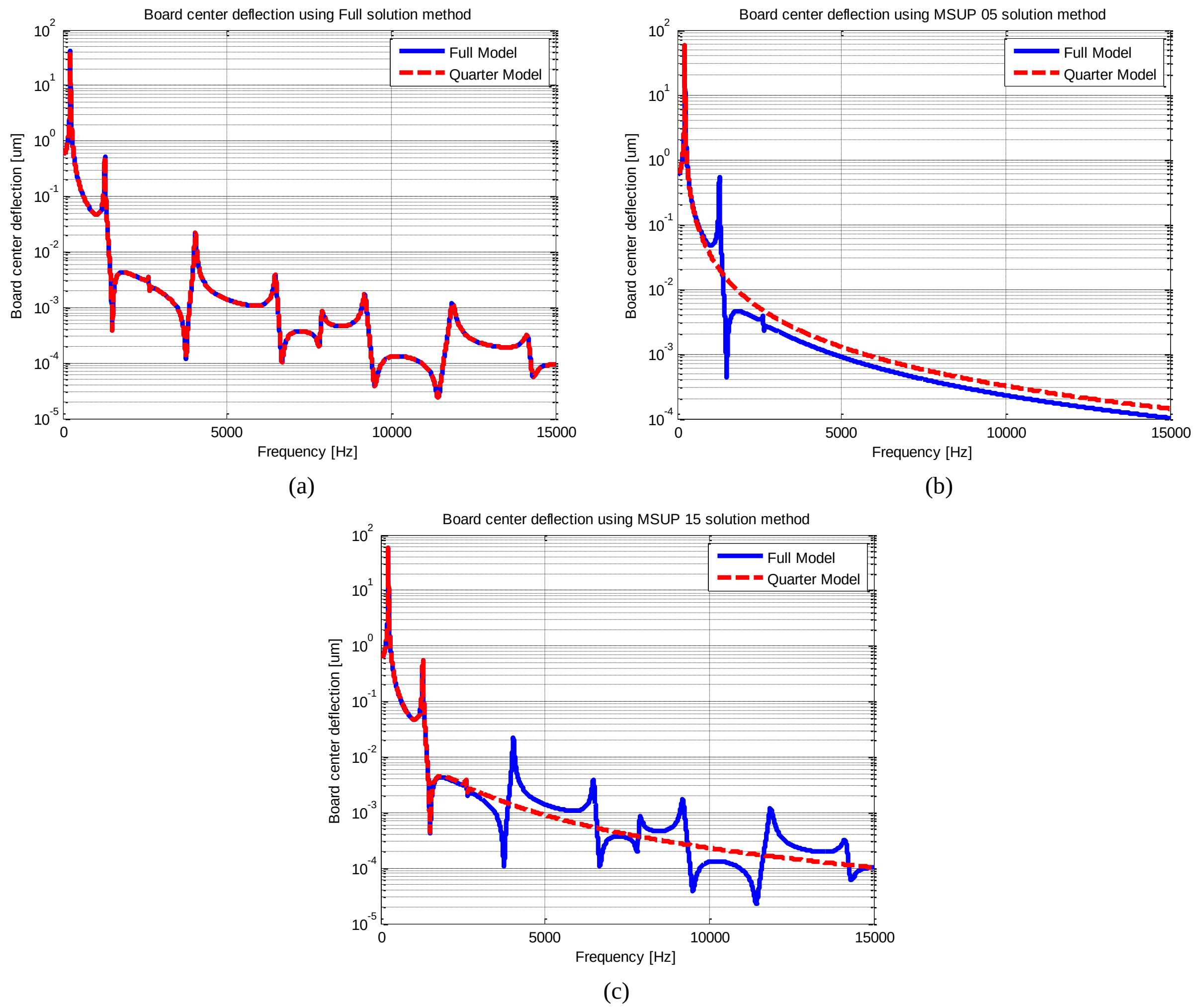


Figure 5. Board deflection frequency response from both full and QS models using (a) full (b) MSUP 05 and (c) MSUP 15 methods.

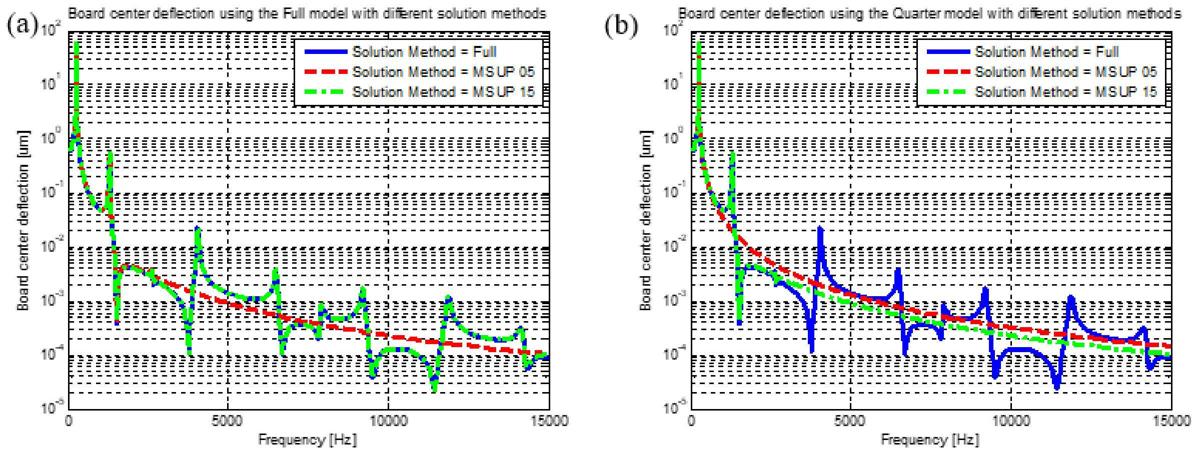


Figure 6. Board deflections frequency response using different solution methods in (a) full and (b) QS model.

4.4. Transient Analysis

The purpose of performing transient analysis in this study is to ensure the validity of using symmetric modes of board-level electronic packages under drop/impact loading. Figure 7 shows the results of the comparison of board transverse deflection time response from both full and QS models using all solution techniques, full, MSUP 05 and MSUP 15. Such findings proves that the results of the symmetry based numerical model perfectly matches those of the full model, for all solution techniques. However, as shown in Figure 8which compares all three solution methods as performed in QS and full models, the use of mode superposition may not yield to the same results of the full solution method, especially after the time exceeds 0.01 seconds. As a result, the use of full solution method is highly favorable for best solution accuracy. Additionally, the adoption of the symmetry based FEA models is also valid and proven to be accurate especially if combined with full solution method.

4.5. Spectrum Analysis

In this paper, the spectrum analysis, or PSD analysis, was used to simulate the random vibration problem of electronic packages at the board-level. As mentioned earlier, the PSD analysis requires the combination of mode shapes which are extracted from modal analysis. Hence, two combinations were investigated in this work: MSUP 05 and MSUP 15 in which 5 and 15 modes were invoked in the solution, respectively. Figure 9 and Figure 10 show the three-sigma (3σ) von Mises stress in the solder area array in both FEA models using MSUP 05 and MSUP 15 solution methods, respectively. The (3σ) von Mises stress means that the probability that solder stresses will exceed this (3σ) stress value is less than 0.3% of the time [39]. This (3σ) von Mises stress value is a commonly used criterion in the fatigue life estimation of electronic assemblies under random vibration [1-2, 29-31, 39]. Back to the stress results, it is shown that the solder stress distributions from the symmetry-based mode and the full model, in MSUP 05 and MSUP 15, and both models proves that the maximum solder stress occurs in the outermost interconnect. Additionally, both full and QS models and solution methods result in the same stress values. For example, the maximum solder stress is 13.7 MPa in all models and solution techniques.

The discussions above prove that the symmetric FEA models are efficient, valid, and safe to use in any of the tested solution methods during the simulation of a spectrum analysis.

4.6. Computational Efficiency

This work introduces a comparison between the symmetry-based and full numerical models in terms of solution time and random-access memory (RAM) usage of the computer machine used throughout the analysis. **Table 4** lists all the solution time and the total RAM usage for all analysis types performed in this study. In general, and as expected, the QS model requires less time and memory than the full model. For example, in static analysis, the QS-to-full-model ratio ($QS/Full$) for solution time is 7.54% and for memory usage is 38.92% which shows great computational advantage of the symmetric model over the full model without losing solution accuracy. Thus, the consideration of symmetry-based numerical models in static analysis type problems is highly encouraged. A similar statement can be made in the use of transient and spectrum analysis types. However, for modal and harmonic analysis, the use of full models is strongly recommended as the solution accuracy is given the priority over the computational costs.

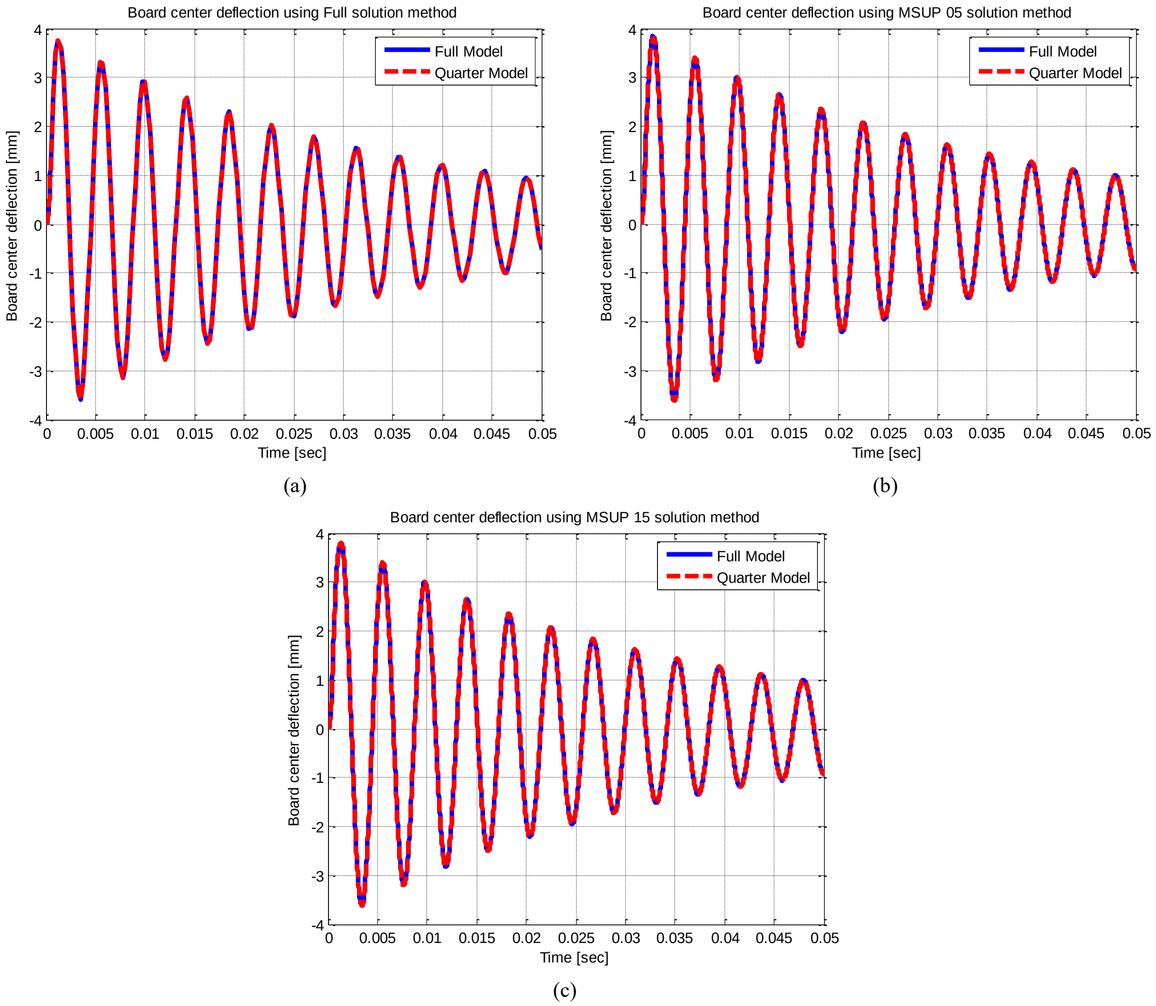


Figure 7. Board deflection time response from both full and QS models using (a) full (b) MSUP 05 and (c) MSUP 15 methods.

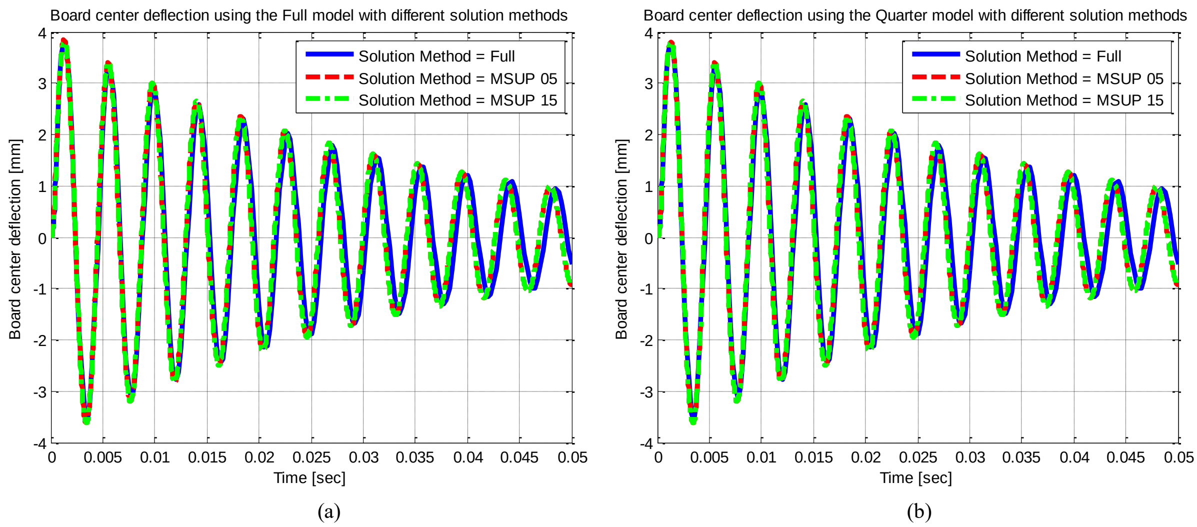
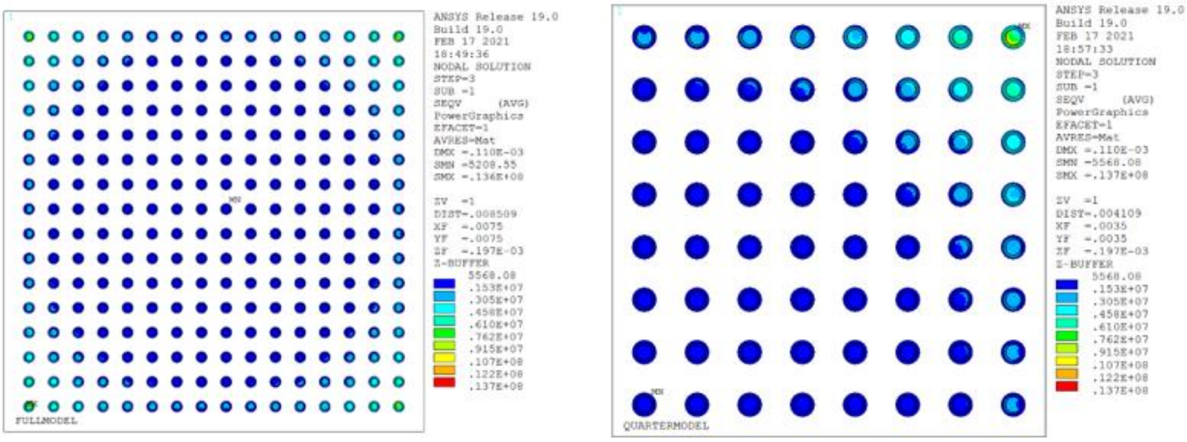
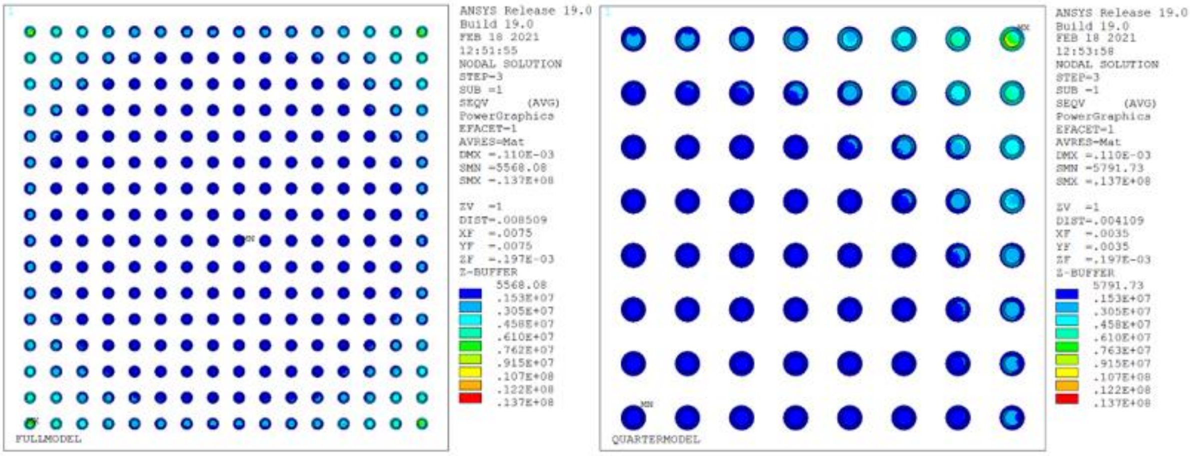


Figure 8. Board deflections time response using different solution methods in (a) full and (b) QS model.



(a) (b)

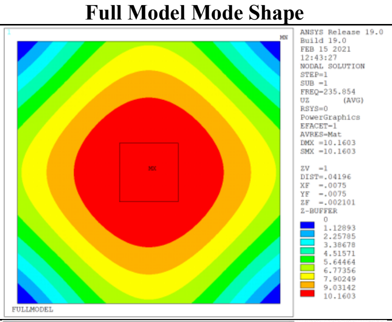
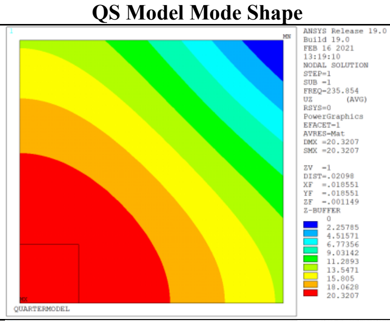
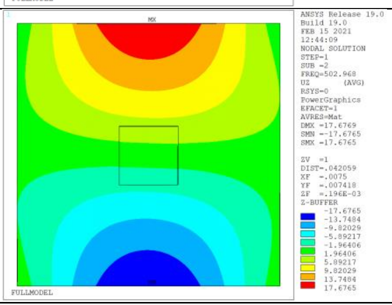
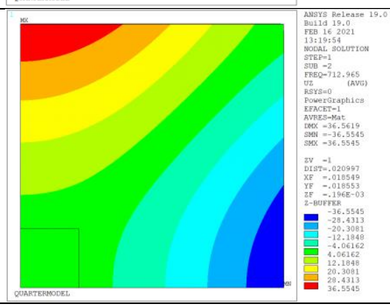
Figure 9. Three-sigma solder area array von Mises stresses using MSUP 05 in (a) full, and (b) QS models.

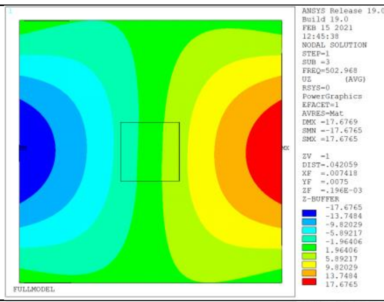
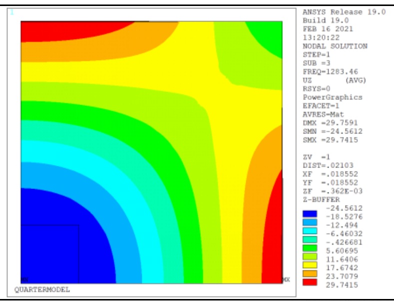
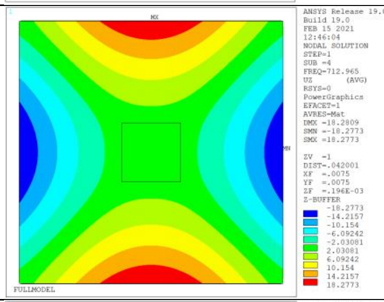
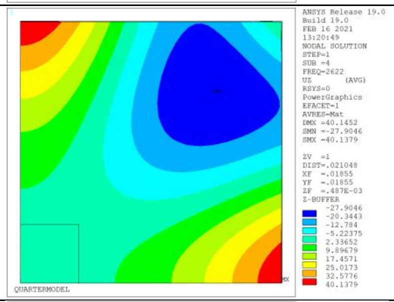
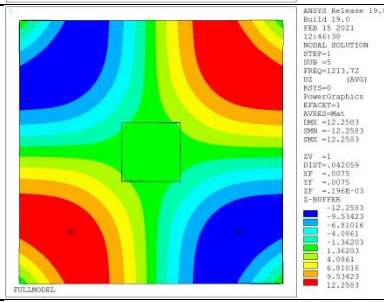
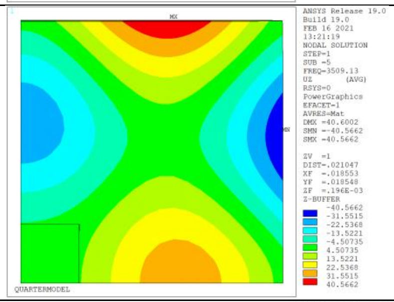
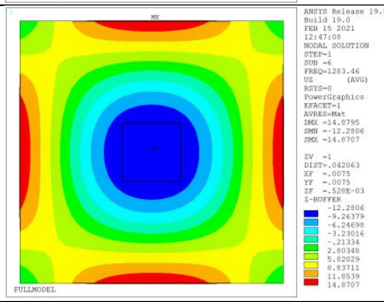
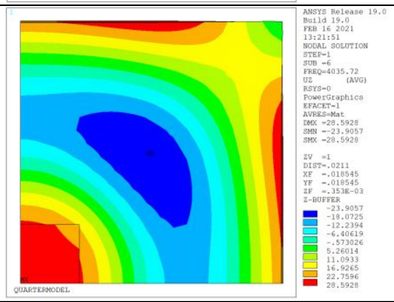
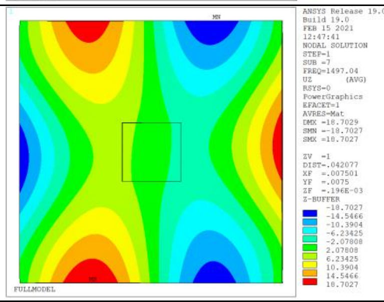
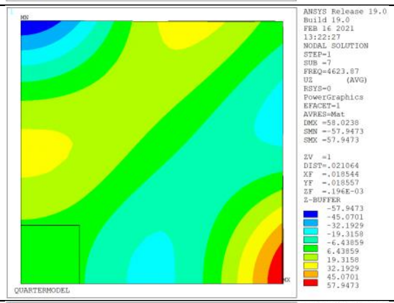
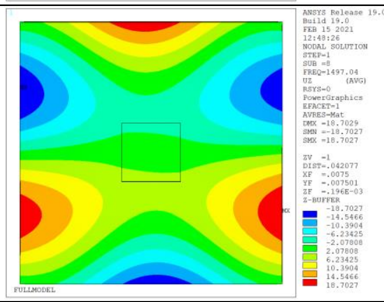
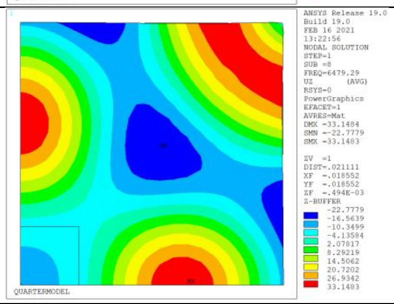


(a) (b)

Figure 10. Three-sigma solder area array von Mises stresses using MSUP 15 in (a) full, and (b) QS models.

Table 3. Mode shape comparison between full and QS models.

Mode #	Full Model Mode Shape	QS Model Mode Shape
1		
2		

3		
4		
5		
6		
7		
8		

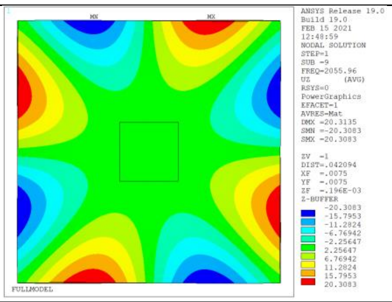
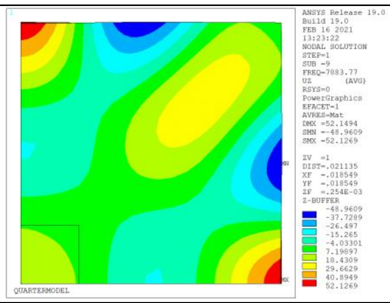
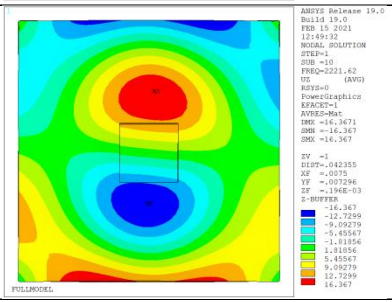
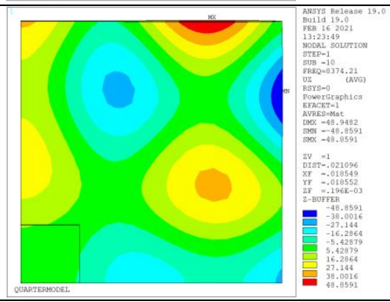
9		
10		

Table 4. Computational efficiency data.

STATIC ANALYSIS			
Model type	**Full Model**	**QS Model**	$\frac{QS}{Full}\times 100\%$
Memory usage (MB)	2549.0	992.0	38.92%
Solution time (sec)	140.6	10.60	7.54%

MODAL ANALYSIS			
Model Type	**Full Model**	**QS Model**	$\frac{QS}{Full}\times 100\%$
Memory usage (MB)	2157	1082	50.16%
Solution time (sec)	106.1	29.9	28.18%

HARMONIC ANALYSIS									
Model Type	**Full Model**			**QS Model**			$\frac{QS}{Full}\times 100\%$		
Solution Method	**Full**	**MSUP 05**	**MSUP 15**	**Full**	**MSUP 05**	**MSUP 15**	**Full**	**MSUP 05**	**MSUP 15**
Memory usage (MB)	2929.0	4590.0	4759.0	2283.0	1764.0	1756.0	77.94%	38.43%	38.43%
Solution time (sec)	395878.6	73.8	180.3	14803.0	10.5	43.2	3.74%	14.22%	23.96%

TRANSIENT ANALYSIS									
Model Type	**Full Model**			**QS Model**			$\frac{QS}{Full}\times 100\%$		
Solution Method	**Full**	**MSUP 05**	**MSUP 15**	**Full**	**MSUP 05**	**MSUP 15**	**Full**	**MSUP 05**	**MSUP 15**
Memory usage (MB)	4885.0	4590.0	4759.0	1500.0	1764.0	1756.0	30.71%	38.43%	38.43%
Solution time (sec)	3298.6	69.9	102.6	730.9	13.9	71.3	22.16%	19.89%	69.49%

SPECTRUM ANALYSIS						
Model Type	**Full Model**		**QS Model**		$\frac{QS}{Full}\times 100\%$	
Solution Method	**MSUP 05**	**MSUP 15**	**MSUP 05**	**MSUP 15**	**MSUP 05**	**MSUP 15**
Solution time (sec)	4158.0	4158.0	1911.0	1903.0	45.96%	45.77%
Solution time (sec)	100.6	253.9	28.0	53.2	27.83%	20.95%

5. Conclusions

This work introduced an accuracy and efficiency study on the use of symmetry-based finite element models of board-level electronic packages subjected to various types of loadings. ANSYS commercial software was adopted in the quarter symmetry model and the full models to perform all the analysis types. Both model types were executed in various problem types including static, modal, harmonic, transient and spectrum analysis. Additionally, solutions methods, as full and mode superposition methods, were considered. Furthermore, this paper reported some data on the computational efficiency metrics including solution time and total memory usage of all model and analysis types conducted. As a result of this study, we recommend the use of symmetric numerical models in static, transient and spectrum analysis types. However, the use of such models is not recommended in eigenvalue problems like modal analysis. For harmonic analysis, a cautious use of the symmetry models, combined with full solution methods, is encouraged. Finally, the computational efficiency results showed high preference in using quarter symmetry models over full models.

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