Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 47 (2023) 757–764

Structural Integrity Procedia

www.elsevier.com/locate/procedia

27th International Conference on Fracture and Structural Integrity (IGF27)

Numerical-experimental characterization of the dynamic behavior of PCB for the fatigue analysis of PCBa

F. Fontana[a], A. Chiocca[a], M. Sgamma[a,*], F. Bucchi[a], F. Frendo[a]

[a] *Università di Pisa, largo Lucio Lazzarino, Pisa 56122, Italy*

Abstract

In today's highly digitized and mechatronics-based world, the need for reliable and cost-effective electronic components has become essential. The reliability of these components is not only based on their electrical and circuit aspects but also on their structural properties. This paper presents a study carried out on two-layer Printed Circuit Boards (PCBs) of rectangular shape, which are representative of many industrial applications. The aim of this study is to compare different numerical models, developed in Ansys Workbench and in a FEM software specifically designed for circuit boards, with experimental tests to determine the most interesting ones for further studies on Printed Circuit Board Assemblies (PCBAs). The comparison includes both static and dynamic behaviors, tested through isostatic bending tests and dynamic analyses with a shaker and a fiber optic laser. The models developed are capable of reproducing statics and dynamics of PCBs with varying degrees of accuracy and numerical complexity. However, increasing the details of the models does not always correspond to an increase in accuracy in reproducing the dynamic behavior. Prior to the experimental dynamic analysis, the influence of constraints' modeling strategies and damping on the first eigenmode was studied, and the results were used to set up tests and simulations to achieve more consistent results. Future work will extend the dynamic characterization to PCBAs by populating the studied PCBs with components, and continue with the study of predictive models for their structural reliability.

Keywords: Numerical analysis; Experimental analysis; PCB; Dynamic; Fatigue; Frequency domain

1. Introduction

Printed Circuit Board Assemblies (PCBAs) are now fundamental components for any system in which any electrical circuit is present. They are responsible for data acquisition, process management, safety control, and everything else that regulates the operation of a system. An example of this is a car, where electronics is crucial to ensure its operation. The market has demanded boards and circuits that are increasingly smaller and subjected to extreme conditions,

* Corresponding author. Tel.: +39-392-956-7676.
E-mail address: michele.sgamma@phd.unipi.it

2452-3216
10.1016/j.prostr.2023.07.043

thus encountering more reliability problems, not only from an electronic point of view, but also from a structural point of view.

Damage to a board at the mechanical level usually occurs for two reasons (Steinberg): the fatigue-related wearing of a component, such as a relay that no longer clicks, or the deterioration of a component's connection to the Printed Circuit Board (PCB), such as a crack in the solder of a pin. The first cause is the rarest and it is addressed by component manufacturers; the second has only been considered in the industrial field since the beginning of the new millennium. Studying the composite material that makes up the PCB, a sandwich of copper and FR4, provides insight into the mechanical properties of the wafer on which the components fit (Bhavsar et al. (2014), Liu et al. (2007), Eswaraiah et al. (2008), Tunhøvd and Per (2014)). Correctly predicting the wafer deformation makes it possible to calculate displacement and deformation fields at the pin anchor zones and to predict their fatigue life. Various authors have modeled PCBAs with more or less complex models to approximate their response to vibration. Pittaresi (Pitarresi (1990), Pitarresi et al. (1991), Pitarresi and Primavera (1992)) and then Wong (Wong et al. (1991), Wong et al. (1993)) are the first to have theorized a "*smeared*" model, wherein the influence of each component presence is accounted for by locally modifying the density and stiffness properties of the board material at areas identified by the component projection onto the board plane. Amy et al. performed studies to develop a methodology that combines vibration failure testing, finite element analysis (FEA) and theoretical formulation for calculating the fatigue life of electronic components, particularly for boards on spacecrafts, which are typically subject to very high vibrations (Amy et al. (2010), Amy et al. (2007), Amy et al. (2009)). In 2022, Morettini and Staffa (Morettini et al. (2022)) published a paper in which they present an evolution of Pittaresi and Wong's models, applied to PyCubed PCBs (open-source printed circuit board used on CubeSat nanosatellites), taking into account the effects of principal components and providing an accurate description of the dynamics. They also generalized the problem, describing a methodology to approximate the dynamic behavior of PCBAs by grouping components into three different categories, depending on mass and size, to which corresponds a different influence on mass, stiffness and damping of the whole board.

The present paper focuses on the study of the standalone PCB to lay the foundation for the study of PCBAs, which will be carried out in future works. In particular, two different types of numerical models of two-layer rectangular PCBs are presented with the purpose of simulating their vibration response. The former type includes simplified analytical-based models, i.e., independent of specific commercial Finite Element (FE) simulation software and computationally lean. The latter identifies models obtained using a specific FE tool for electronic boards and PCBA reliability studies, which will be referred to in this paper as eFEM software. According to the existing literature and with some preliminary tests made for this work, the most critical mode shape for PCBA failures is the first one (Steinberg). For this reason, the goal of this work is to provide a simple and reliable tridimensional model of the PCB, which can accurately approximate its dynamic behavior, with particular attention to the first eigenmode. The models have been validated through an extensive experimental campaign, including both static and dynamic tests, performed on test machines and shakers. In future works. the most suitable models will be enhanced with various types of electronic components in order to investigate their fatigue resistance.

2. Materials and methods

2.1. Numerical Models

As part of this work, five different numerical models of the PCB, shown in Figure 1, were developed and compared with each other. Two of them, that will now on be addressed as *simplified models*, were developed by the authors on analytical considerations and can be implemented and solved on any FEM simulation software. On the other hand, the remaining three models are closely related to the use of the specific eFEM (electronics Finite Element Method) software that was used to develop them, namely ANSYS Sherlock. Sherlock is a package specifically designed to make fatigue life predictions of PCBAs. It stands out for the possibility of directly importing eCAD (electronic Computer-Aided Design) models, that contain information on board design, in terms of both geometry and material composition as well as information on electronic components and soldering. Although it does not allow static structural analysis, the eFEM software makes it easy to solve modal dynamics problems and to obtain fatigue life estimations of electronic boards subjected to loads of various kinds (harmonic, random, shock, or thermal) based on probabilistic considerations. That is, once the load on the electronic board has been determined, the eFEM software provides fatigue life

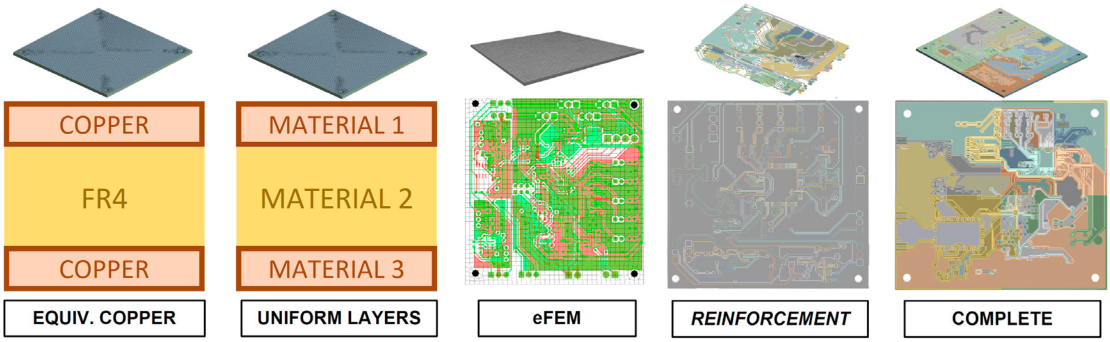


Fig. 1: Implemented numerical models.

results in terms of probability of failure as a function of time of use. A further advantage of ANSYS Sherlock is the capability to export and solve the mechanical model of the board in ANSYS Workbench, thus providing more direct control over the boundary conditions, meshing, and reliability of the results obtained.

All models have been used to replicate the isostatic bending test and to solve the modal and harmonic problem by calculating the first five natural frequencies and their modal shapes. To make the comparison more homogeneous, all models were setup with *brick* elements and constrained using a *fixed support* applied to the nodes at the interface surface with the constraint screws. Below is a more detailed description of each model:

- *Equivalent Copper*. It is the simplest model, since it uses three rectangular layers to model the board geometry: a central layer of FR4, and two outer layers of copper. The thickness of the copper layers h_{Cu} can be analytically calculated with equation 1, thus uniformly distributing the actual mass of copper m_{Cu} on the board surface A (ρ_{Cu} is the density of copper).

$$h_{\mathrm{Cu}} = \frac{m_{\mathrm{Cu}}}{A\,\rho_{\mathrm{Cu}}} \tag{1}$$

- *Uniform Layers*. In this model, the layers of the PCB keep their actual thickness, but to each of them is assigned an equivalent homogeneous material, whose properties (e.g. density, elastic modulus, thermal conductivity) are calculated according to rule of mixtures (equation 2), where p_i is a property of the i-th layer equivalent material, and $v_{\mathrm{mat}_j,i}$ is the volume fraction of the j-th material in the i-th layer of the PCB.

$$p_i = \sum_j p_{\mathrm{mat}_j,i} v_{\mathrm{mat}_j,i} \tag{2}$$

- *eFEM*. This model is fully designed and simulated in the eFEM software interface. The model is automatically created importing the PCB eCAD and only need to be assigned the Mounting Points and the type of analysis to be performed. The low computational effort required by the software allows to use the most accurate type of mesh, that assigns a different material to each element created. Material properties are computed based on the percentage of materials actually contained in the corresponding element.
- *Reinforcement*. Every layer of the PCB is modeled as an homogeneous layer of FR4, that is then merged with a *Trace Model* exported from the eFEM software, that contains information about the actual traces of copper contained in the PCB layer. This *Reinforcement* process (so called due to its similarity to concrete reinforcements) is carried out in ANSYS Workbench environment, which is then used to carry out the numerical simulations.
- *Complete*. From a given eCAD, the eFEM software allows to create and export a FE model almost identical to the PCB. The model includes all the bodies that make up the board, and each of them is automatically assigned his specific material. Once created in the eFEM interface, the model can be exported and simulated into ANSYS Workbench similarly to the previous model.

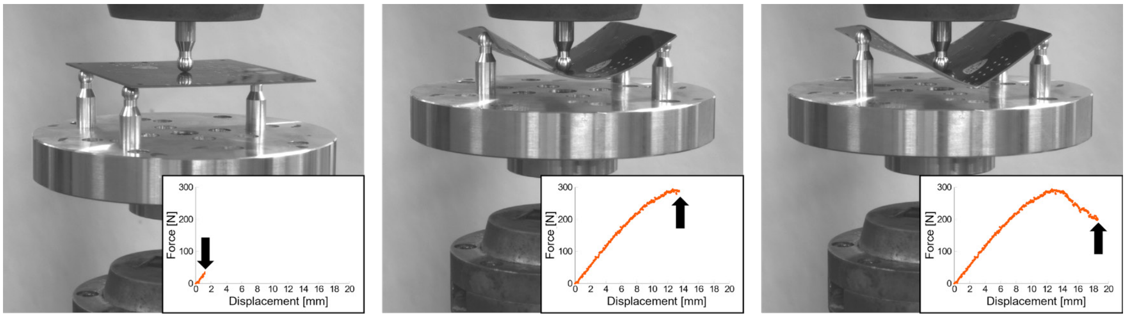


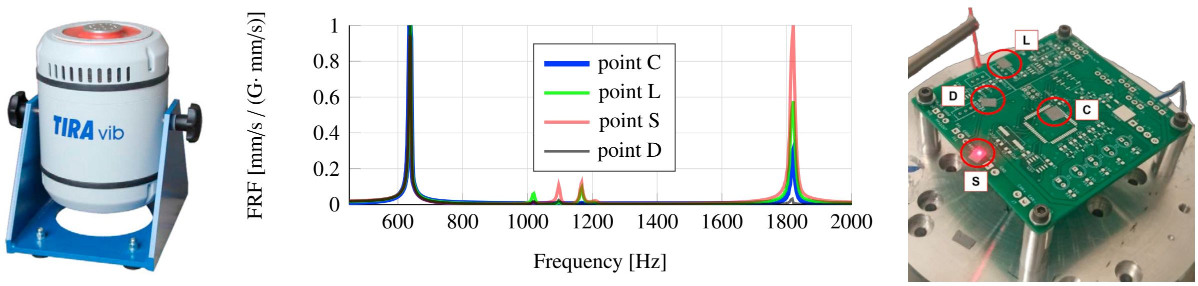
Fig. 2: PCB static test (from left): test start; high board deformation and local imprinting; board breakage and test ending.

2.2. *Isostatic bending tests*

The purpose of the isostatic bending test is to evaluate the stiffness of the board and the mechanical behavior of the PCB in quasi-static loading condition. The test consists of driving a spherical-headed punch, which loads the PCB lying on three supports, also spherical-headed, deforming it until the failure occurs. Figure 2 shows a sequence of pictures taken during the test (starting from the left): test start; very deformed board and local imprinting starts; board breakage and test termination. A hydraulic test machine is used in displacement control at very low speeds (0.04 mm/s) so that it can be considered a quasi-static test. The result is the force-displacement curve shown in Figure 2. The chosen configuration, which differs from a classical three-point bending test, is an isostatic constraint with respect to vertical loading. This choice allows to simplify the numerical modeling of the test boundary conditions, since it removes the line-contact issues encountered in a three-point bending test configuration.

2.3. *Dynamic tests*

In order to observe the dynamic behavior of the PCBs, a sine sweep test has been performed. The main purpose was to determine the eigenfrequencies of the boards and their Frequency Response Function (FRF), together with the main factors that influence their dynamic behavior. The test was carried out using a vibrating shaker (Fig. 3a) that imposes the desired acceleration with a feedback control performed by an accelerometer placed on the base plate. The boards were subjected to a harmonic load in acceleration, with an amplitude of $9.8\,\mathrm{m\,s^{-2}}$, by making a slow sweep over the desired frequency range (200-2500 Hz). The PCB is constrained by means of four M3 threaded screws to aluminum spacers (Fig. 3c), which are inserted and attached to an interface plate, that allows different types of boards to be tested on the shaker. A fiber optic laser (sampling rate: 24 MHz, spot: 4.0 µm) samples the speed of various points on the PCB surface, allowing to calculate its dynamic response. The test result, when normalized with respect to the acceleration imposed by the shaker, corresponds to the FRF relative to the point on the board whose vibration



(a) (b) (c)

Fig. 3: Dynamic test: vibrating shaker (a); computed FRF (b); PCB mounting and sample points (c).

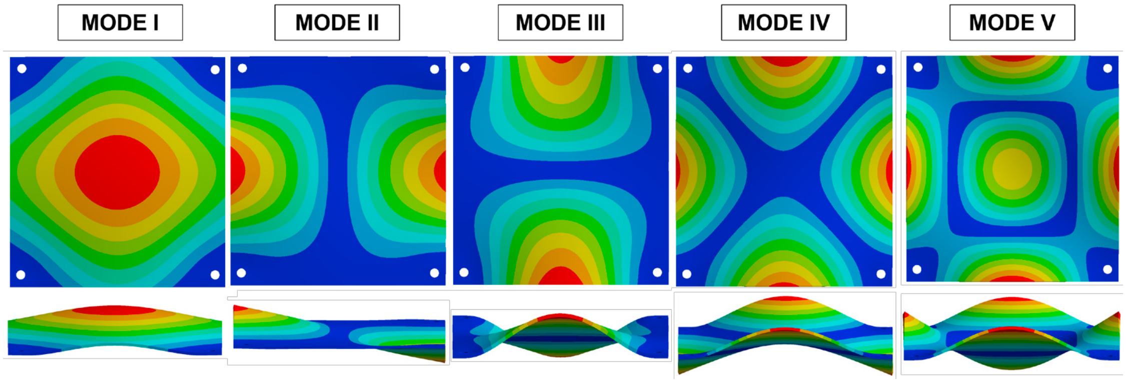
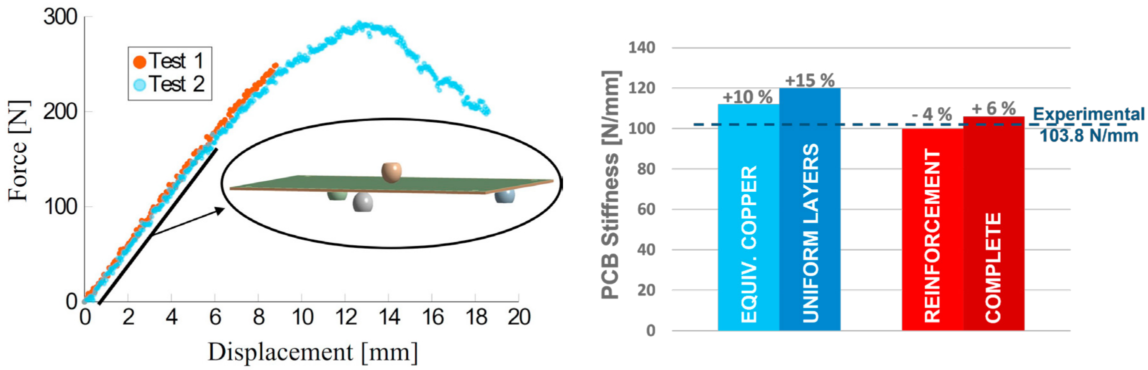


Fig. 4: First five mode shapes of the Printed Circuit Board.



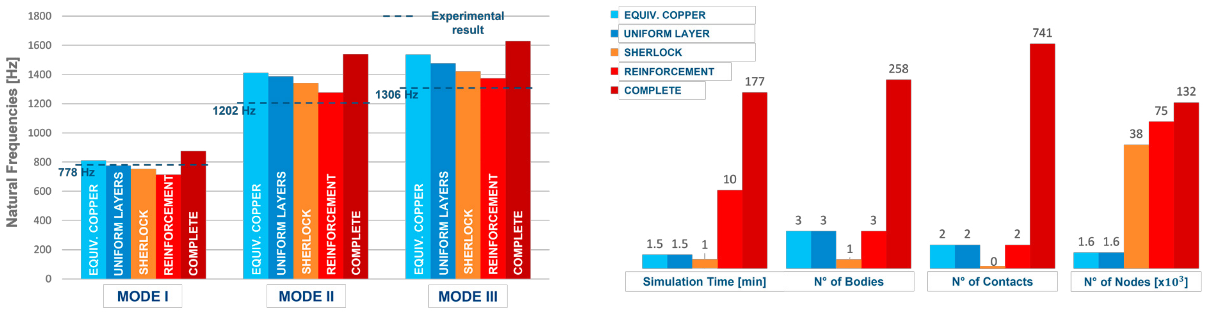
(a) (b)

Fig. 5: Static test results: Static curves of the PCB from experimental tests (a); comparison between numerical and experimental results for PCB stiffness (b).

is measured. Figure 3b, where the curves are normalized to their maximum for easy reading, shows the results of the tests for four different points (C, S, D and L) of the same PCB. It is worth noting that sampling at different points on the board is necessary to be sure that all the PCB eigenfrequencies are correctly identified. This is due to the fact that some of the chosen sampling points may fall close to nodal lines of one or more of the modal shapes of the board (Fig. 4), and consequently may not be affected by any vibration when the board is stressed at the frequencies related to those modes. For example, referring to Figure 4, the center of the board (point C) experiences a displacement only in the first and fifth modes of the PCB, while it remains stationary in the intermediate modes, since the center of the board is on a nodal line for eigenmodes 2 to 4. Correspondingly, in Figure 3b the curve for the measurement at point C gives only two peaks at the first and fifth eigenfrequencies, showing good numerical-experimental correlation.

3. Results and Discussion

Figure 5a shows the resuts of the isostatic bending tests. The initial linear behavior of the PCB is soon lost due to a combination of factors, including a local indentation due to the punch and the constraints and the loss of linearity of the behavior of the entire PCB. Two tests were carried out for each board, obtaining relative errors of no more than 4% on the slope of the linear section. Figure 5b shows a comparison between experimental stiffness and stiffness obtained by the different numerical models for one of the tested PCBs, considering only the linear part of the experimental



(a) (b)

Fig. 6: Numerical-Experimental comparison of resonance frequencies of the PCB (a) and comparison between the computational effort required for the models (b).

tests. Results are consistent with the degree of detail of each model. The two simplified models provide the least accurate results, while the more complex reinforcement and complete models considerably improve the estimation. As mentioned in the previous section, the eFEM software does not allow to perform static structural analysis, thus the eFEM model is not included in the comparison. Despite the simplified models cannot perfectly reproduce the PCB stiffness, the important outcome is that all models provide reasonable values of bending stiffness, as it lays the foundation for having good results in dynamic simulation of the models, which is the main purpose of the work. In addition, more in-depth modeling of the punch-board contact is likely to lead to better results for static analysis as well.

Table 1: Average percentage error of numerical models with respect to experimental results on the first three eigenfrequencies.

Mode no.	Equivalent Copper	Uniform Layer	eFEM	Reinforcement	Complete
I	3.9%	1.3%	1.7%	6.5%	7.4%
II	7.4%	10.0%	8.8%	3.0%	18.1%
III	7.6%	6.5%	4.6%	3.6%	15.4%

Coming to the results of the dynamic tests, Figure 6a shows a comparison between the first three eigenfrequencies obtained by experimental tests on one of PCBs and the results obtained by simulating the numerical models. Considering all results, Table 1 reports the average percentage error on the first three eigenfrequencies and shows that all models provide a fairly good approximation of the first mode of the boards. Interestingly, based on the results of the boards used, the best results for the first eigenfrequency are those provided by the simplest models, and in particular the uniform layer model among the simplified models and the eFEM model among those derived from the specific eFEM software, and both provide errors of less than 2%. For higher eigenfrequencies, almost all models increase the error on the approximation of the eigenfrequency value, except for the reinforcement model, which has an error of less than 4% and becomes the model that most accurately approximates the second and third eigenfrequencies of PCBs. A separate discussion should be made for the complete method, for which errors shown in the table are significantly higher than the other models and do not match the degree of complexity of the model. This is probably due to the fact that the complete model requires a very large number of input parameters to be entered, which in some cases may not be known or precisely determinable (e.g., modeling of the contact between copper traces and FR4). Therefore, entering default or other unconfident values for such parameters, when not available, can lead to inaccurate results.

Histograms in Figure 6b shows several values indicating the computational effort required by the models. The complete model is significantly heavier and time-demanding in terms of simulation, which combined with the factors described above has led to its withdrawal. In contrast, the most computational-efficient models are, as expected, the two simplified models and the eFEM model, which require very low simulation times and a small number of bodies and contacts. As for the Reinforcement model, despite it provides good results with a low number of bodies and contacts to model, requires an order of magnitude more time for simulation than the simpler models, which is not reflected in a similar improvement in results, especially for the first eigenfrequency of the PCBs.

4. Conclusions

The present work led to the development of various numerical models to study PCB dynamics and it is easily applicable to PCBAs. Five different numerical models have been created and compared. Two of them, called simplified models, were developed by the authors based on analytical relationships and can be implemented on any FEM simulation software, while the other models were developed using a specific eFEM software, that is also necessary to perform numerical simulations. Results from numerical simulations have been compared with experimental data to determine the most suitable models to be used in future works to perform fatigue life estimations on PCBAs. All models provide good approximations of the experimental results for both the static and dynamic behavior of PCBs. However, the significant computational demand and the high number of calibration parameters required by the more complex models have led to a preference for lightweight and easy-to-implement models.

A brief account for each model analyzed is given below.

- *Equivalent Copper*. It is the simplest model to implement and simulate because of the small amount of information required (only the PCB geometry and the percentage of copper). It is based on simple analytical relationships and can be used with any FEM simulation software. Despite its simplicity, it succeeds in reproducing both the statics and dynamics of electronic boards with good approximation. In addition, the low number of parameters involved allows for a greater control over the model, making it possible to easily understand whether the result represents an overestimation or underestimation of the real properties of the board and to correct any possible problems.
- *Uniform Layers*. Like the previous model, it is based on simple analytical relationships and can be used with any FEM software. Compared to the Equivalent Copper model, it has the advantage of taking into account all the materials present in the layers, which allows it to obtain a better approximation of the dynamic behavior of the board. As a result, it provides a better accuracy/simplicity ratio, as it improves the approximation of dynamic results with low computational effort and requiring a low amount of information, such as the PCB geometry and the volumetric percentages of the board materials.
- *eFEM*. Although it does not allow static structural analysis, this model manage to obtain a very good description of PCB dynamics with high computational efficiency and the lowest simulation time. However, its weak points are the fact that it can be solved only using the specific eFEM software, and that it requires the complete eCAD model of the circuit board, which is not always available or easily achievable. Despite that, it has considerable potential in the perspective of reliability analysis of PCBAs, and it will be further considered in future developments of this work.
- *Reinforcement*. This model provides very good results for the static properties of the PCB and for the determination of eigenfrequencies higher than the first. However, it is a quite complex model, since it requires the full eCAD model of the PCB and it is far more time consuming than the simpler models (both for modeling and simulation phases). These drawbacks led to the decision to not further use this model in future developments of this work, since the goodness of the results, especially concerning the first and most important eigenfrequency, is not high enough to justify its use over the simpler models.
- *Complete*. It is a very complex model since it requires detailed modeling of the geometry, material properties, and contacts within the board. For this reason, it is the most demanding both in terms of computational effort and in the amount of information required. It allows for good static characterization, but the large number of parameters, which are not always known or accurately determinable, can lead to inaccurate dynamic results.

The obtained results allow the next step of testing printed circuit board assemblies to assess the ability of the most effective numerical models, namely the Equivalent Copper, Uniform Layer, and eFEM models, to approximate their dynamic behavior when equipped with an electronic component. Furthermore, fatigue testing will be performed on simplified PCBAs (comprising a single soldered component) to evaluate the precision of reliability predictions offered by the eFEM software and compare them with the commonly used analytical models.

Acknowledgements

This paper is supported by the Ministry of University and Research (MUR) as part of the PON 2014-2020 “Research and Innovation” resources – Green Action - DM MUR 1062/2021 - Title of the Research: Sviluppo e riconversione di dispositivi automotive in ottica green: la decarbonizzazione dei veicoli e nuovi impieghi dei sistemi termo-idraulici.

References

Amy, R.A., Aglietti, G.S., Richardson, G., 2007. Sensitivity analysis of simplified pcb fe models. Proceedings of the 1st CEAS European air and space conference CEAS-2007-466 .

Amy, R.A., Aglietti, G.S., Richardson, G., 2009. Sensitivity analysis of simplified printed circuit board finite element models. Microelectronics reliability 49, 791–799.

Amy, R.A., Aglietti, G.S., Richardson, G., 2010. Accuracy of simplified printed circuit board finite element models. Microelectronics Reliability 50, 86–97. URL: https://www.sciencedirect.com/science/article/pii/S0026271409003515, doi:https://doi.org/10.1016/j.microrel.2009.09.001.

Bhavsar, N., Bhat, M., Bhavsar, N.R., Shinde, H.P., Pune, C., Specialist, T., 2014. Determination of mechanical properties of pcb. International Journal on Mechanical Engineering and Robotics .

Eswaraiah, C., Kavitha, T., Vidyasagar, S., Narayanan, S., 2008. Classification of metals and plastics from printed circuit boards (pcb) using air classifier. Chemical Engineering and Processing: Process Intensification 47, 565–576.

Liu, F., Meng, G., Zhao, M., 2007. Viscoelastic influence on dynamic properties of pcb under drop impact. Journal of Electronic Packaging, Transactions of the ASME .

Morettini, G., Staffa, A., Mancini, E., Dionigi, M., Cianetti, F., Braccesi, C., 2022. Simplified fe modeling of the pycubed pcb complete with components for cubesat missions. Journal of Space Safety Engineering 9, 328–340. URL: https://www.sciencedirect.com/science/article/pii/S2468896722000660, doi:https://doi.org/10.1016/j.jsse.2022.06.004.

Pitarresi, J., Caletka, D., Caldwell, R., Smith, D., 1991. The” smeared” property technique for the fe vibration analysis of printed circuit cards. Journal of Electronic Packaging, Transactions of the ASME .

Pitarresi, J.M., 1990. Modeling of printed circuit cards subject to vibration. IEEE International Symposium on Circuits and Systems , 2104–2107 vol.3.

Pitarresi, J.M., Primavera, A.A., 1992. Comparison of modeling techniques for the vibration analysis of printed circuit cards. Journal of Electronic Packaging, Transactions of the ASME .

Steinberg, D., . VIBRATION ANALYSIS FOR ELECTRONIC EQUIPMENT. WILEY-INTERSCIENCE.

Tunhøvd, H.E., Per, D., 2014. Characterization of the material properties of two fr4 printed circuit board laminates.

Wong, T.L., Stevens, K.K., Wang, G., et al., 1991. Experimental modal analysis and dynamic response prediction of pc boards with surface mount electronic components. Journal of Electronic Packaging 113, 244–249.

Wong, T.L., Wang, J., Stevens, K.K., 1993. Automated Hybrid Analysis of Surface Mounted Electronic Assemblies. Journal of Mechanical Design 115, 435–440. URL: https://doi.org/10.1115/1.2919208, doi:10.1115/1.2919208, arXiv:https://asmedigitalcollection.asme.org/mechanicaldesign/article-pdf/115/3/435/5920352/435_1.pdf.