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AN INFORMATION-DRIVEN FEA MODEL GENERATION APPROACH FOR CHIP PACKAGE APPLICATIONS

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ABSTRACT

In the electronic chip package development process, Finite Element Analysis (FEA) modeling is widely used as a virtual prototyping technology to achieve good designs. Due to the complexity and variability in materials, geometric shapes, and connectivity configurations, etc. in a chip package, FEA modeling is a tedious and time-consuming activity. Typically finite element modeling takes hours or even days to complete an analysis for a single chip package design. The Multi-Representation Architecture (MRA) is presented as a framework to facilitate automatic transformations of design models into analysis models through four stepping-stone information representations: (1) analyzable product models (APM), (2) context-based analysis models (CBAM), (3) analysis building blocks (ABBs), and (4) solution method models (SMMs). The ABB models describe theoretical physical systems while SMMs represent the ABB models in solution technique-specific form, such as FEA.

In this paper, we present an information-driven FEA modeling approach facilitating the mapping between ABBs and SMMs by first decomposing the geometry into meshable bodies and subsequently generating vendor-specific SMMs. To demonstrate this FEA modeling approach, a chip package thermomechanical analysis example is given. The information-driven FEA modeling approach is shown to be an effective and efficient method for capturing engineering information in chip package products, as well as decreasing FEA modeling time.

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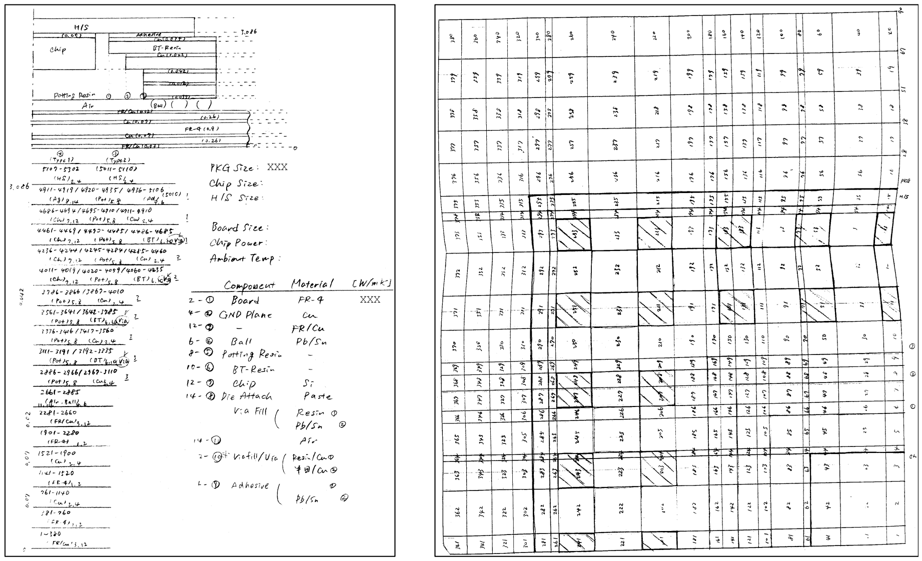
Keywords: Multi-Representation Architecture (MRA), Analysis Building Block (ABB), Ready to Mesh Model (RMM), Solution Method Model (SMM), Constrained Object (COB), Variable Topology Multi-Body (VTMB), Finite Element Analysis (FEA), and Design Analysis Integration

1. INTRODUCTION

The increasing competition in chip package industry forces engineers to develop high quality chip packages in faster and cheaper ways. This creates needs for new technologies and approaches facilitating seamless design and analysis integration. In this paper, we focus on the integration of chip package design using Finite Element Analysis (FEA). The finite element method is one of the most widely accepted analysis technologies because of its efficacy in simulating the operational behaviors of packages, such as thermal resistance, thermomechanical stress distribution and electromagnetics performance. The key factor in enabling analysis driven design is the integration of design and analysis techniques. This requires the transformation from design models to FEA analysis models. However, a typical chip package consists of at least tens of components that have variable materials, complex geometric shapes and changeable connectivity configurations. Moreover, traditional FEA modeling approaches are geometry-based approaches; the analyzable mesh model of a chip package is generated based on the geometric features of the components in the package. Hence, every time when the package design is modified, the FEA modeling has to be repeated manually by experienced engineers. It is a tedious and time consuming process that usually takes hours or even days for a single design.



Analysis Concepts Geometry Preparation for Mesh Generation

Figure 1. FEA Model Planning Sketches in Traditional Approach

A traditional FEA modeling scenario is shown in Figure 1. In the beginning, an analyst sketches the analysis concepts of the chip package, shown on the left side of the figure, which contains all the necessary information for FEA modeling, including SHAPE, dimensions, materials, boundary conditions and etc. Then, to obtain the meshable geometry for multi-body applications, the analyst has to make geometric preparation using the two-dimensional projection template for extrusion as shown on the right side of Figure 1, the extruded model represents the geometric model after mental decomposition for meshing purpose. Hence, the sketch provides visual aids to manually prepare the geometry in a FEA commercial package.

Complexity of such models is caused by factors including the following [1]:

1. Various considerations necessitate the use of idealized geometry in such simulations (e.g., mesh complexity, solution time, lack of details in early design stages, and improved simulation).
2. Even so, accurate chip package analysis models must consist of a number of idealized bodies (e.g., 20-30 bodies) of different idealized materials (e.g., 10 or so). The finite element method requires nodes match between these bodies.
3. These bodies are tightly packed together. Thus the meshing of one body can strongly impact the meshing of bodies that are not directly adjacent to it, as shown in Figure 2. We use the term coupled variable topology multi-body (VTMB) model [2] to describe this type of problem. Typically labor-intensive “chopping” is required to transform the analytical model into an FEA geometry model that can then be properly meshed.
4. The idealized bodies may not be part of the patterns that are regularly repeated *en masse*.
5. The geometric idealizations that are significant for simulating one type of behavior may not be the same as those for another (e.g., stress vs. temperature).

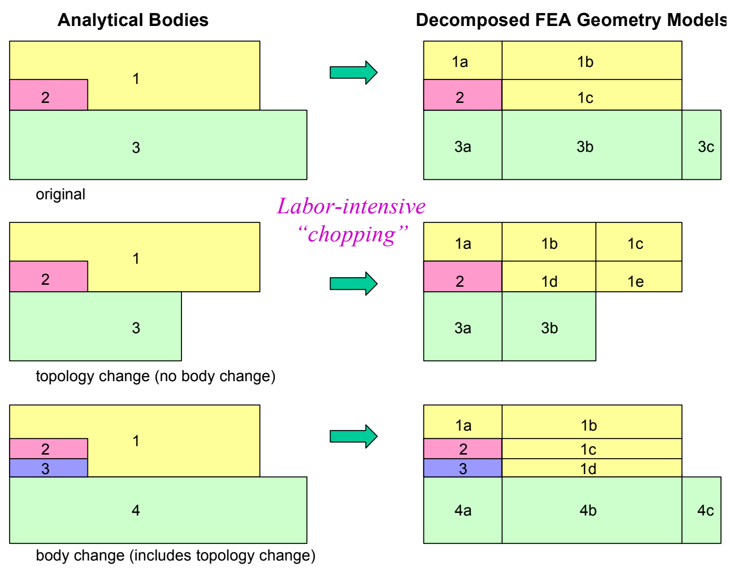


Figure 2. Characteristics of VTMB FEA Models

Moreover, the mesh models are barely reusable by using this traditional approach due to the fact that small topology changes force the mesh model to be rebuilt from scratch. In order to automate the modeling process to save the modeling time and reduce the human errors, to increase reusability of the mesh models during chip package modification and redesign, information-driven analysis template and composable analysis module based systems are developed. These achieve the

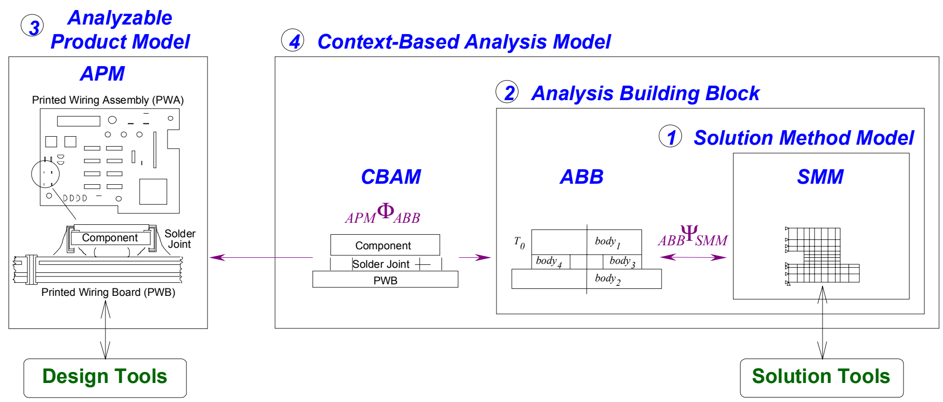


Figure 3. Multi-Representation Architecture [4] for Design-Analysis Interoperability

automatic generation of mesh models to some degree [3]. However, these approaches are still ineffective to be adaptable to topology and assembly configuration variations caused by changes of product design, analysis disciplines, and idealization processes.

In this paper, we present an information-driven FEA modeling approach for chip package applications on the basis of a design and analysis integration methodology proposed by Peak and colleagues, Multi-Representation Architecture (MRA) [4], Section 2. The MRA consists of four stepping-stone information representations, *i.e.* analyzable product models, context-based analysis models, analysis building blocks (ABBs), and solution method models (SMMs). ABBs and SMMs are product-independent models facilitating generalized mappings between a single product model and diverse analysis models. The ABB models, introduced in Section 3.1, describe the theoretical physical systems, such as continuum mechanics systems. It allows users to define FEA models by high-level information-driven analysis building blocks to capture the engineering analysis concept. The information-driven FEA modeling approach introduced in this paper facilitates automatic mapping between ABB models and SMMs by presenting an intermediate ready-to-mesh model (RMM) in Section 3.2. The geometry of RMMs is easily meshable by the available meshing techniques in the current generation of commercial tools. To transform ABBs to RMMs, a decomposition process, Section 3.3, is presented to decompose the assemblies of analysis building blocks into fine-grained low-level models – RMMs. SMMs, Section 3.4, represent ABBs and RMMs in relatively low-level solution technique forms, such as finite element analysis models. By this approach, the analysis building blocks can be easily assembled to accommodate the variable topology change and assembly configuration change; FEA modeling process can be implemented in a full automatic manner. Finally, in Section 4, an engineering case is presented to explain this approach and demonstrate its efficacy.

2. FRAME OF REFERENCE – MRA

The MRA is illustrated using a solder joint thermomechanical analysis example in Figure 3. On the right side is a solution method module (SMM), marked with ①, which represents an analysis model in relatively low level and solution method specific form. An SMM combines solution tool inputs, outputs, and control into a single information entity to facilitate automated solution tool access and results retrieval. Analysis building blocks (ABBs), marked with ②, represent analytical engineering concepts in a manner that is largely independent of product application and solution method. ABBs obtain results by generating SMMs through transformations, $_{ABB}\Psi_{SMM}$, that are based on solution method considerations. Analyzable Product Models (APMs), marked with ③, represent detailed design-oriented product information. An APM is considered the master description of a product which supplies information to other product life cycle tasks, including engineering analysis and manufacturing. To enable its usage by potentially many analysis applications, an APM in the MRA goes beyond its traditional design role by supporting idealizations that relate detailed design-oriented attributes with simplified analysis-oriented attributes. Finally, a context-based analysis model (CBAM), marked with ④, contains linkages that represent design-analysis associativity between an APM and an ABB model, $_{APM}\Phi_{ABB}$. These associativity linkages indicate the usage of idealizations for a particular analysis application (e.g. solder joint deformation). Thus, CBAMs show how product independent ABBs are supplied with design-related information to help solve product-specific analysis problems.

From the MRA viewpoint, providing solutions to the design-analysis integration problem involves defining these four representations (SMMs, ABBs, APMs, and CBAMs) and two inter-representation mappings ($_{ABB}\Psi_{SMM}$ and $_{APM}\Phi_{ABB}$). Since the focus in this paper is the information-driven FEA modeling approach, the boundary of such topic is limited to the process design for $_{ABB}\Psi_{SMM}$ and information modeling for the information flow.

3. INFORMATION-DRIVEN FEA MODELING APPROACH

The information-driven FEA modeling approach presented in this paper is targeted to model the analysis concepts as ABB models and automate the generation of FEA based SMMs. This approach involves the process design and the corresponding information modeling. Generally, this approach should be capable of supporting the variable topology and multi-body FEA modeling for the chip package applications. To save the modeling time, automated process is desirable and the reusability of previous models is preferable. Furthermore, the conformable hexahedral mesh should be achievable for high quality of hexahedral elements relative to tetrahedral elements.

It is difficult to achieve direct mapping from FEA modeling concepts (ABBs) to FEA models (SMMs) because of the complexity of the mesh generation process. This complexity is caused by factors such as shapes, analysis disciplines, interconnect configurations, material, elements, etc. All these factors contribute to the final geometry and topology representation of the FEA model. As the result, typically, the representation ends up with variable topology multi-body FEA models. Currently, parameterized mesh template based technique supports a direct mapping between ABBs and SMMs. However, analysis templates are topology dependent and are generally limited to the class of applications with limited topology change [3]. Therefore, a small topology change will force the analysis templates being rebuilt from scratch. Driven by broader applications with variable topology and multi-body characteristics, we partitioned the ${}_{ABB}\Psi_{SMM}$ mapping into two simplified sub-mapping processes, as shown in Figure 4.

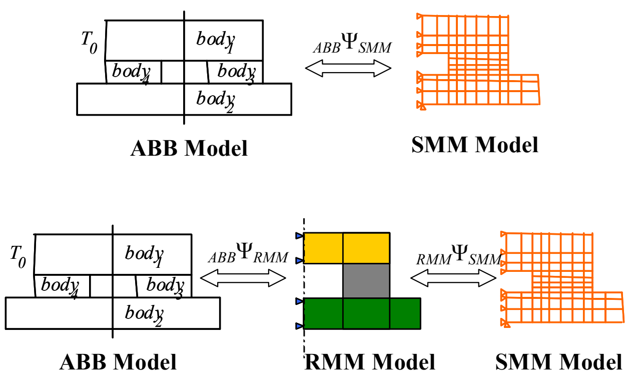


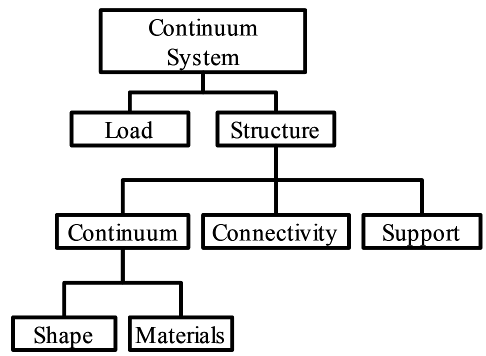
Figure 4. Information-Driven FEA Modeling Approach

The first mapping process ${}_{ABB}\Psi_{RMM}$ transforms the ABB model into a ready-to-mesh model (RMM). The mapping process is an intuitively geometry decomposition process that mocks up the FEM domain discretization process. The subsequent mapping process ${}_{RMM}\Psi_{SMM}$ transforms the RMM into the solvable FEA based SMM in an automated manner. The FEA based SMM is expressed in a script file format where the pre-processor, solver and post processor information are integrated together. In this way, full automation can be achieved using FEA commercial tools.

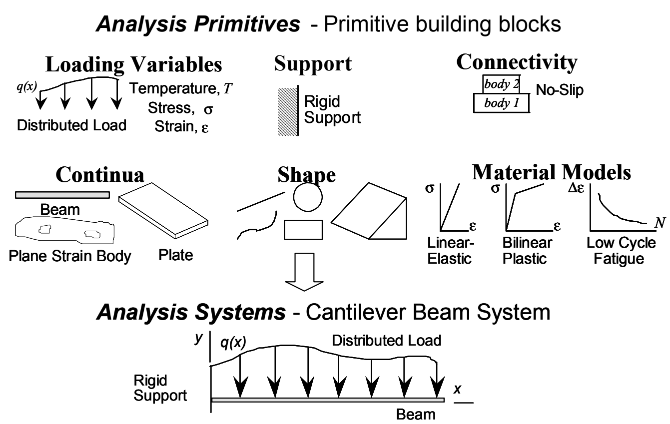
The individual models and processes will be explained in Section 3.1 to Section 3.4 in details.

3.1 Analysis Building Block Models

An ABB model represents engineering analysis concepts as a set of computable information entities, which are independent from specific solution techniques [4]. In the context of solid mechanics and thermal systems, ABB concepts are presented in Figure 5. To facilitate representing a variety of continuum systems, ABB information content is categorized by the composition in Figure 5a. A continuum system consists of two key components: idealized structure and idealized loads. Structure represents any assembly of objects that supports or transmits loads, *e.g.* idealized building structure, aircraft, vehicles, etc. Loads represent active forces that are applied onto the structure because of external causes, *e.g.* pressure, vibration, temperature, and etc. [5]. Both these aspects in the composition hierarchy are necessary to completely represent a continuum system.



a. Composition Hierarchy for ABB Continuum Systems



b. ABBs Catetorized by Type [1,2]

Figure 5. Information Content for Example ABB Concepts

At the next level, structure is composed of individual continua, and the interrelations between those continua are described using connectivity concepts (idealized interconnections). For instance, slip bonding between two continuum entities indicates the condition that the two continuum entities are in contact, while only relative displacement along the contact interface is allowed. Relative displacement interrelations between a structures and its environment are identified as support constraints such as rigid support, pin support, etc. ABBs are categorized by types into several levels, including analysis primitives that are used in building intermediate ABBs and analysis systems (Figure 5b). For instance, shape and material models are primitive ABBs; they are combined together with other ABB concepts to represent a continuum ABB – an intermediate type of ABB primitive. An ABB system, as shown in Figure 5b for a cantilever beam analysis system, is formed by assembling ABB primitives such as a loading force, a continuum beam, and a rigid support.

In the composition hierarchy given in Figure 5a, the leaf nodes denote analysis primitive categories at the levels where they can be easily changed or reused in a plug-and-play manner, and the root node represents an ABB analysis system. Hence, an ABB model is composed of fundamental building blocks to represent all the necessary information in an analytical sense.

The modularity of ABB information content helps to capture the analysis knowledge by employing object technology and constraint graph concepts, such as constraint objects (COBs) [6]. The COBs modeling language provides modularity, reusability and multi-directionality, and closely matches the way engineers interpret their interactions with an idealized environment. By mapping each item in the ABB concept hierarchy, Figure 5a, into a corresponding object type in COBs, the complete information of a class of continuum systems can be described. The lexical format of ABB information objects is explained in detail in Zeng, et al. [7].

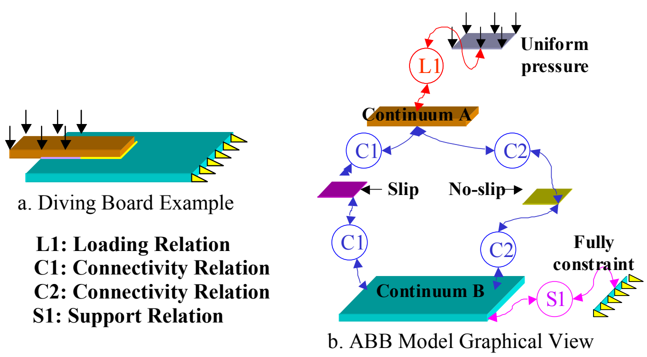


Figure 6. A Graphical View of an ABB System and its Analytical Bodies and Connectivities

To explain the concept of ABB models, a graphical view of an ABB system is shown in Figure 6. The diving board is composed of two continuum building block instance objects, namely, Continuum A and Continuum B. The properties of connectivity between these two continua are not uniform. A portion of the interconnect region is slip bonded while the remainder is no-slip bonded. To explain this situation with mixed types of interconnects, two interconnect property instance objects, Slip and No-slip, are presented. Two connectivity instance objects C1 and C2 connect Continuum A to Continuum B. The boundary conditions applied on the diving board are the uniform pressure on top of continuum A and zero displacement at the end of continuum B. Similar to the connectivity definition, the property instance objects of boundary conditions are defined and associated with the corresponding continuum by the loading instance object L1 and support instance object S1. This example ABB system is used in the following sections to demonstrate the process from ABB to SMM in a step-by-step manner.

3.2 Ready-to-Mesh Models

The RMM model is generated by manipulating the ABB geometry, and is ready to be meshed by computationally inexpensive meshing techniques. Meanwhile, the mesh compatibility along the interconnect interfaces is ensured. Moreover, the geometric representation for the RMM is dependent on the meshing techniques. For instance, parametric geometry for an ABB is appropriate for mapped mesh; hence the geometry for RMM is prepared in the way that it can be easily mapped to a mesh model. Non-manifold geometry of an ABB undergoes proper geometry decomposition to obtain a RMM and finally to be transformed into quadrilateral or hexahedral mesh. Meanwhile, solid geometry of an ABB is better to get hexahedral mesh with volume decomposition to obtain a RMM. In this context, since ABB and RMM information objects supports the representation of non-manifold geometry and solid geometry, geometric decomposition is an feasible geometry manipulation approach.

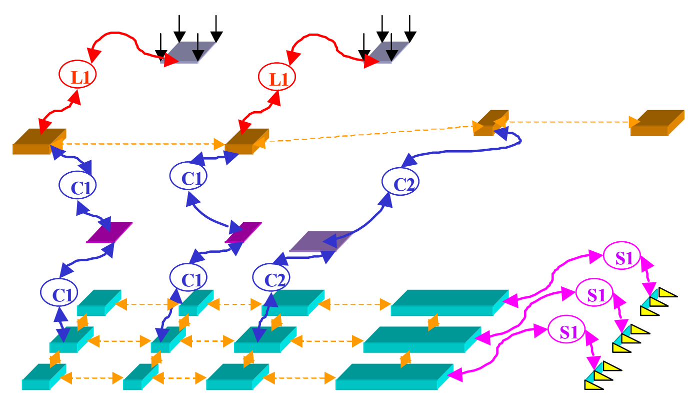


Figure 7. A Graphical View of an RMM System and its Decomposed Bodies and Connectivities

In order to distinguish the building blocks of ABB from those of RMM, the building blocks to construct the RMM model are termed as granules according to their relative small geometric scales in comparison with those constructing the ABB model. Geometric decomposition affects the entire ABB system because of the fact that the building blocks in an ABB system are all associated with the geometry. For instance, in Figure 7, Continuum A is broken down into four continuum instance granules. Similarly, Continuum B is broken down into 12 continuum instance granules. As a result, connectivity instance objects (C1 and C2) and boundary instance objects (L1 and S1) are also decomposed to adapt to the geometry change. Prior to decomposition, continuum A is connected with Continuum B, and after decomposition, some continuum instance granules from Continuum A will no longer be connected to any instance granule from Continuum B. Additionally, the specialty of decomposing the continuum is that the new non-slip connectivity instance objects are constructed to interconnect the decomposed continua, which is represented by the doted arrows in Figure 7.

The transformation between a RMM model and a SMM model can be easily achieved in an automated manner. The geometry of the RMM model is composed of geometry pieces that are convex-shaped and meshable using efficient and cheap meshing techniques such as mapped meshing. The building blocks that construct an ABB model can be reused to construct a SMM model due to several reasons. Firstly, the geometric decomposition doesn't change the properties of the building blocks. For instance, continua are still continua after decomposition, even with different shapes. Secondly, granules are subsets of the ABB building blocks because of their much simpler geometry shapes and hence the ABB information representation objects can be reused as that for the RMM. Additional discussion about how to represent the linkage between the original ABB and the decomposed ABB, i.e. RMM is carried out in the next section.

3.3 Decomposition Architecture

Typically, to generate a solvable FEA model, intensive efforts are invested in the manipulation of geometry to obtain a desirable mesh. For multi-body model in chip package application, geometry decomposition is implemented beforehand to facilitate the generation of conformal mesh along the interfaces of connected bodies. The RMM is generated by this decomposition process, therefore the complexity of the ABB geometry is reduced to easy the conformal mesh generation. This step is especially important to generate hexahedral mesh. The decomposition result is non-unique and determined by the factors such as decomposition algorithm applied, topological and geometrical characteristics of input geometry, and desirable decomposed geometry, etc. For the chip package application in this paper, the decomposition process ideally ends up with an assembly of decomposed bodies where those connected bodies meeting along equivalent faces. One of the reasons of selecting this decomposition model is that intuitively geometry decomposition process mocks the FEA discretization process. Moreover, 'glue' or 'chop' operation is the easiest Boolean operation that can be mentally and manually handled. This is also a very popular geometry manipulation method for analysts before the geometry can be input directly for computation. So, it acts as a convincible decomposition algorithm template that helps accomplish these mental and manual works automatically.

The flow chart of the decomposition algorithm is shown in Figure 8, which is impacted by the work of Liu and Gadh[8]. Geometry and topology feature recognition is a reasoning process to determine where the decomposition starts. The separator is generally a surface based on which the geometry will be decomposed; and decomposition can be implemented by Boolean operations. The decomposition involves iterative operations until the desirable meshable shape is obtained. The details of the algorithm are anticipated in the future publications.

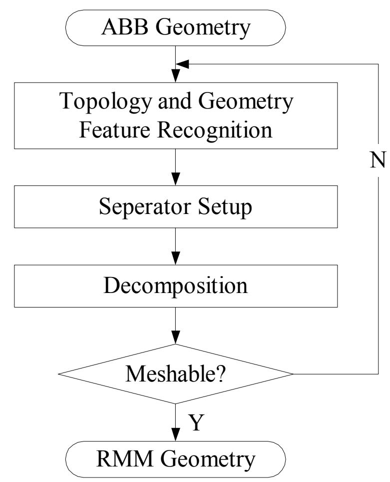


Figure 8. ABB Geometry Decomposition Process

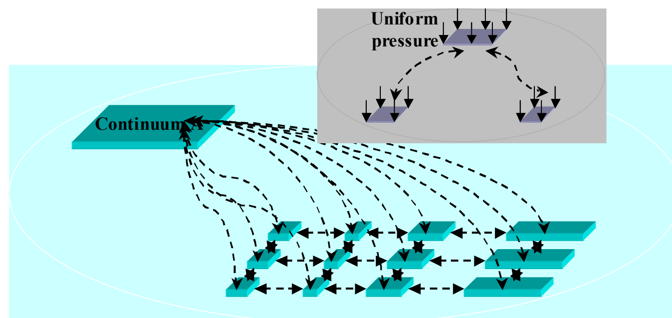


Figure 9. Compositional Relations for Boundary Condition Building Blocks and Continuum Building Blocks after Decomposition

The geometry is manipulated exclusively during the decomposition process. However, the effects of geometry change propagate to the information objects, which depend on the specific changed geometry, such as continua associated with that geometry, loads, assigned upon that geometry etc. The corresponding information associativity with the geometry will be lost without a mechanism that keeps track of the information associativity during the geometry decomposition. For instance, a continuum has a block shape with material copper. After decomposition, the block may be dissected into several blocks; but engineers would still need to know the materials of those blocks. Therefore, a composition mechanism is required to keep track of the associativity throughout the decomposition process. In Figure 9, exemplified compositional relations are shown for boundary condition building blocks and continuum building blocks before and after decomposition.

The RMM information objects represent the direct model data input for the FEA solution process, based on which, a SMM model is generated as computable format for FEA commercial packages.

3.4 Solution Method Models

General FEA solution process is shown in Figure 10. Figure 11 is the technical view of this process in MRA framework.

Figure 10. FEA Solution Process

A solution method model is defined as an information entity that wraps these tool inputs and outputs into a single logical package. In the case of FEA, an SMM is not just a pre-processor of input file but it also includes files that control the solution tool, and the results themselves. SMM includes the SMM information objects and the SMM tool agent. Information objects in this case represent the information required for mesh control and postprocessor control. Tool agents serve as automated tool wrappers. Hence a tool agent performs tasks such as determining the solution tool instances to be used, preparing the input for the solution tool, and running the solution tool. After obtaining the results, the tool agents interpret the results and populate the corresponding SMM instance objects with the results.

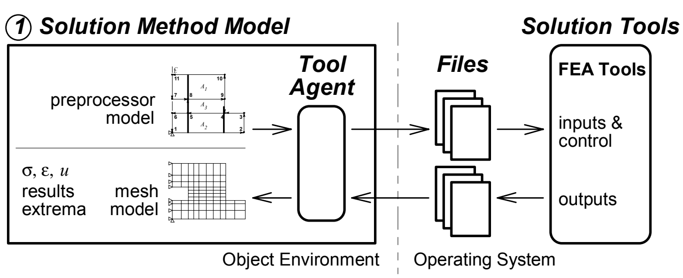


Figure 11. Solution Method Model [4]

Overall, with ABB model capturing engineering analysis concepts, the decomposition process helps to prepare the RMM. SMM represents the RMM combined with control information in a computable format for the FEA commercial packages, such as ANSYS, PATRAN etc.

4. A CHIP PACKAGE THERMOMECHANICAL ANALYSIS CASE

A simplified chip package thermomechanical analysis case is presented to illustrate this information-driven FEA modeling approach. Thermomechanical failures are caused by stresses and strain within a chip package due to thermal loading from the environment or internal heating [9]. It is one of the most important failure mechanisms that need to be considered in package design.

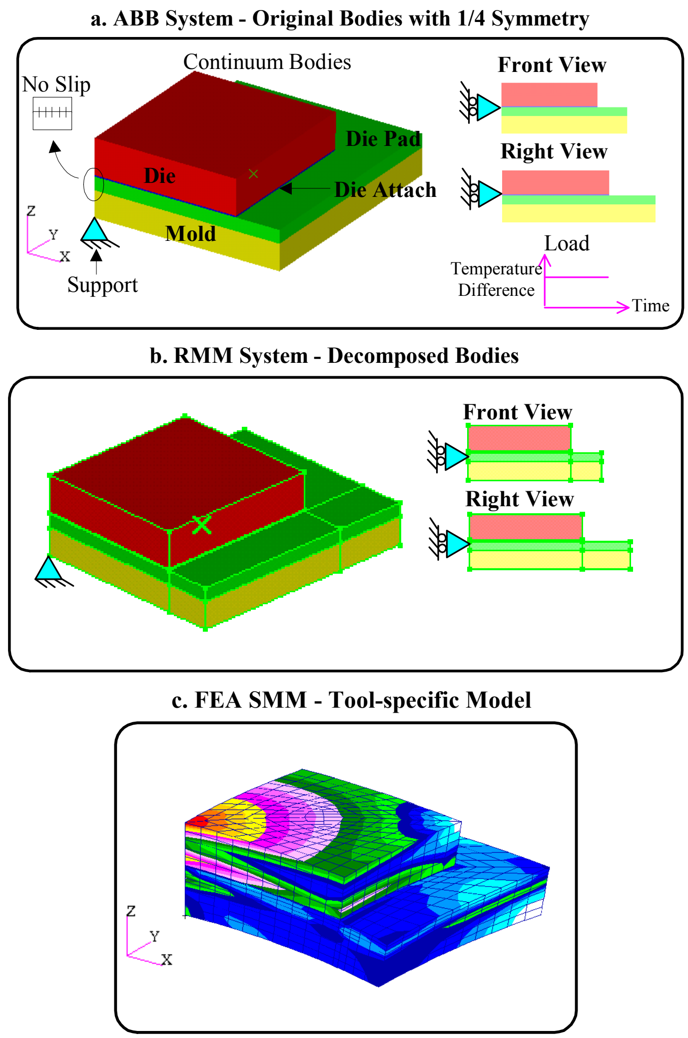


Figure 12. A Thermomechanical FEA Modeling for Chip Package

Given an idealized chip package, a graphical view of the thermomechanical ABB analysis system is shown in Figure 12a. The structure is composed of four linear elastic thermomechanical continua (i.e., die, die attach, die pad and mold), which are glue bonded in the idealized sense (i.e. no slip) to form a stackup. The supports of this structure are a rigid pin support at the corner point of the mold and roller pin supports on all the surfaces that are located in the XZ (front view) and the YZ (right view) planes of the coordinate system. The load applied on the structure is a uniform temperature difference, which generally causes thermal stresses as CTE (coefficient of thermal expansion) mismatches typically exist among the material models in such ABB systems. As shown in Figure 12b, a RMM is displayed that the geometry of original ABB has been decomposed. To obtain this model, automatic decomposition is implemented. With the help of the composition mechanism, the information associated with geometry such as materials, connectivity (no slip), displacement constraints (roller pin support) can be assigned on the corresponding decomposed geometry. This model can be directly input into the SMM to generate a conformal FEA meshed model. The results from FEA SMM are illustrated in Figure 12c. To obtain this analysis result, the tool agent translates the model information into the tool-specific computable formats such as a PATRAN command language (PCL) ASCII file. This input file is then sent to a commercially available FEA package, in this case PATRAN. Finally, the results are extracted one the analysis is complete.

Using this approach, the modeling time traditionally spent on creating a specific finite element model is transferred to the creation of information instance objects. For this case, the FEA modeling using the traditional model planning approach (Figure 1) takes approximately 3 to 4 hours, while using the proposed approach, it takes only 25 minutes. The pilot usage indicates that FEA modeling time can be reduced up to a ratio of 10:1, from days/hours to minutes [10].

5. CLOSURE

In this paper, we present an information-driven FEA modeling approach. The MRA design-analysis integration architecture which laid the foundation of ABBs, SMMs and ${}_{ABB}\Psi_{SMM}$, was illustrated in Figure 3. The system view of the approach is shown in Figure 4. This approach provides rich information representations for the analysis concepts like the ABB model in Figure 5 and Figure 6. To bridge the information gap in mapping from ABBs to SMMs, RMMs are introduced (Figure 7). To obtain RMMs from ABBs, the decomposition process is designed such that the geometry decomposition algorithm (Figure 8) and composition mechanism (Figure 9) are the key techniques. The Concept of general FEA solution process (Figure 10) is embodied in SMMs. SMMs facilitate automated solution tool access and results retrieval as shown in Figure 11. Using the thermomechanical analysis of a chip package (Figure 12), we demonstrate that the proposed approach is capable of representing product-independent analysis concepts as a set of semantically rich, reusable, modular, and tool-independent objects. VTMB applications are facilitated by this information-driven approach, and the overall FEA modeling time is reduced from days/hours to minutes. Overall, experiences to date indicate that this approach provides a better knowledge capture and increases automation versus traditional direct FEA modeling approaches.

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REFERENCES

[1] Peak, R.S., Matsuki, R., Wilson, M.W., Koo, D., Scholand, A.J., Hatcho, Y., and Zeng, S., (2001), "An Object-Oriented Internet-based Framework for Chip Package Thermal and Stress Simulation," *The Pacific Rim/ASME International Electronic Packaging Technical Conference and Exhibition*, Kauai.

[2] Koo, D. (2000). "A Product Data-Driven Methodology for Automating Variable Topology Multi-Body Finite Element Analysis," Master Thesis, Mechanical Engineering, Georgia Institute of Technology, Atlanta.

[3] Peak, R.S., Scholand, A.J., Tamburini, D.R., and Fulton, R.E., (1999), "Towards the Routinization of Engineering Analysis to Support Product Design, Invited Paper for Special Issue: Advanced Product Data Management Supporting Product Life-Cycle Activities," *Intl. J. Computer Applications in Technology*, Vol. 12, No. 1, pp. 1-15.

[4] Peak, R.S., Fulton, R.E., Nishigaki, I., and Okamoto, N., (1998), "Integrating engineering design and analysis using a multi -representation approach," *Engineering with Computers*, 14, 2, pp. 93-114.

[5] Gere, M.J. and Timoshenko, P.S., (1997), *Mechanics of Materials*, PWS Pulishing Company, Boston.

[6] Wilson, M. (2000). "Constrained Object Representation for Engineering Analysis," Master's, Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.

[7] Zeng, S., Peak, R.S., Wilson, M.W., Matsuki, R., and Xiao, A., (2003), "Analysis Building Blocks-A Rich Information Model Context for Knowledge-Based Finite Element Analysis," *Second MIT Conference on Computational Fluid & Structural Mechanics (CFSM)*, Cambridge, MA.

[8] Liu, S.S. and Gadh, R., (1998), "Basic LOgical bulk shapes (BLOBs) for finite element hexahedral mesh generation to support virtual prototyping," *Journal of Manufacturing Science and Engineering-Transactions of the Asme*, 120, 4, pp. 728-735.

[9] Rao, T., (2001), *Fundamentals of Microsystems Packaging*, McGraw-Hill, New York.

[10] Matsuki, R., Peak, R.S., Zeng, S., Wilson, M.W., Kim, I., and Bajaj, M., (2002), "Design-Analysis (Thermal and Mechanical) Integration Research for Electronic Packaging," *SEMICON Japan 2002 Press Conference*, pp. 62-73, Chiba, Japan.

