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A MULTI-REPRESENTATION APPROACH TO CAD/CAE INTEGRATION: RESEARCH OVERVIEW

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Introduction

In today's product design process, a significant gap typically remains between detailed computer aided design (CAD) models and computer aided engineering (CAE) models. While many aspects of engineering analysis are computation-intensive, we believe CAD/CAE integration is primarily an information-intensive problem that requires engineering information management solutions. The purpose of this section is to overview our research aimed at providing such solutions, to introduce some clarified terminology, and to make known the primary literature. Other potential applications of the underlying information technology are also discussed.

Multi-Representation Approach

Fundamentally, we believe the gap between design and analysis models is generally too big for a single integration bridge. Hence, we have developed a **multi-representation architecture** (MRA)[1] which places two information stepping stones between these two extremes. Figure 1 summarizes this multi-representation architecture (using solder joint thermomechanical analysis as an example) and numbers each representation for ease of reference.

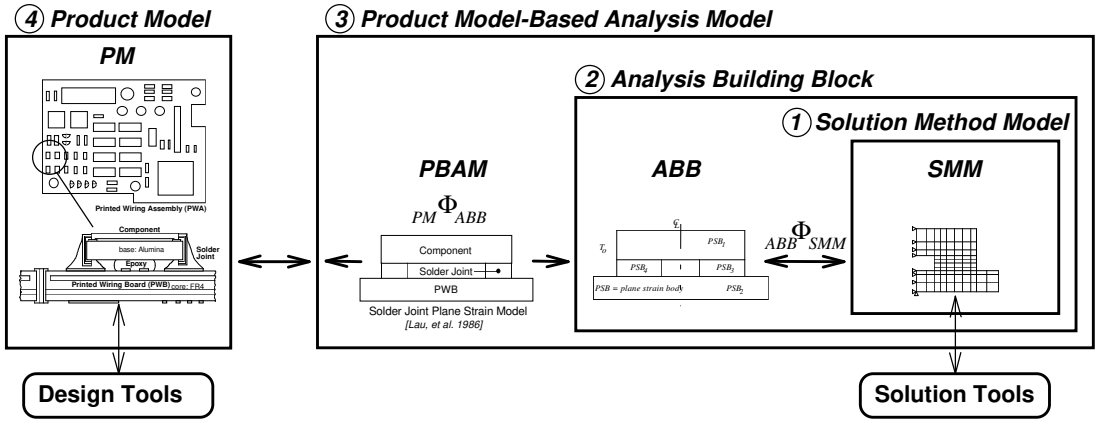

Figure 1 The Multi-Representation Architecture for CAD/CAE Integration

On the right extreme are **solution method models** (① SMMs) representing analysis models in detailed, solution method-specific form. SMMs combine solution tool inputs, outputs, and control into a single information entity which can automate solution tool access and results retrieval. For example, an SMM for a typical finite element analysis (FEA) tool includes the preprocessor model as a tool input and the mesh model and stress extrema as outputs.

Analysis building blocks (② ABBs)[2] represent engineering analysis concepts in a manner that is largely independent of any particular product application and solution method. Figure 2 summarizes the

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1 Basically what was originally called the "PBAM approach" viewed from a broader perspective, with more clearly defined representation interrelationships.

2 The acronyms ABB and PBAM originally stood for "*analytical* building block" and "product model-based *analytical* model" respectively. ABBs and PBAMs are indeed "analytical" in the sense that they represent concepts in an "exact" form; however, the original terminology tended to lead people to believe that only models with analytical solutions could be handled. Therefore, the term "analysis" is now used to convey the original intent

two main types of general purpose ABBs: analysis primitives and analysis systems. ABBs obtain results by generating SMMs through transformations, ${}_{ABB}\Phi_{SMM}$, that are based on solution method considerations (e.g., symmetry and mesh density). Furthermore, because a variety of solution tools exist even for the same solution method (e.g., for FEA: Abaqas, Ansys, Nastran and others), the same ABB can produce a corresponding variety of SMMs. Thus, in a nutshell, ABBs act as semantically rich "pre-preprocessor" models to engineering solution tools.

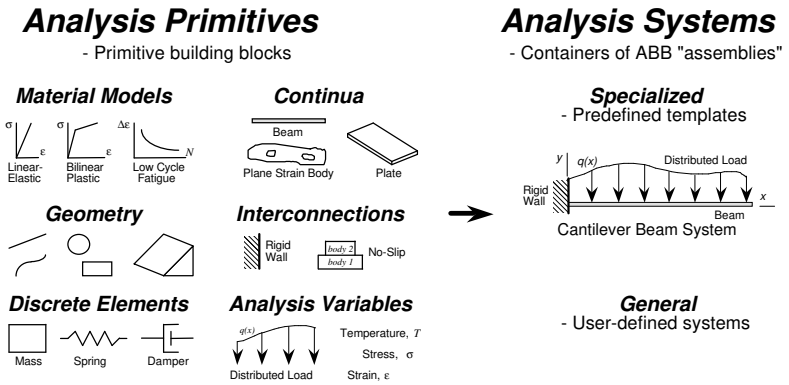

Figure 2 Categories of General Purpose ABBs

The ABB representation is an information modeling template combining constraint graph theory and object-oriented principles to represent analysis concepts. Thus, a specific type of ABB (e.g., Linear-Elastic Material Model) is defined by a populated **ABB structure** - the complete description of the analysis concept in textual form. Figure 3 shows graphical and tabular information views that contain subsets of the ABB structure. These views aide the development, implementation, and usage of ABBs. For example, **object relationship diagrams** use STEP EXPRESS-G notation to show ABB attributes and ABB hierarchies, while a new notation called **constraint schematics** (analogous to electrical schematics) graphically emphasizes constraint relationships among objects.

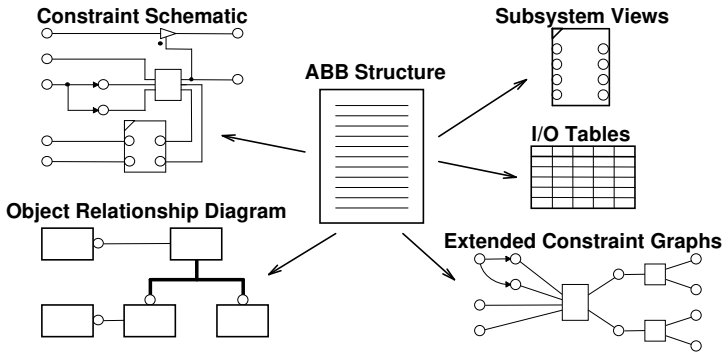

Figure 3 Structural Views in the ABB Representation

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with hopefully less confusion. Similarly, the two main types of general purpose ABBs are now called "analysis primitives" and "analysis systems."

Skipping to the left extreme of Figure 1, **product models** (④ PMs) represent detailed, design-oriented product information. A PM is considered the master description of a product which supplies information to other product life cycle tasks, including engineering analysis and manufacturing. PMs also include relationships between detailed, design-oriented attributes and simplified, analysis-oriented attributes for usage by potentially many analysis applications. These relationships are what others have called **analysis idealizations**, Γ, and include simplifications such as finding total dimensions and determining the primary material in a multi-material part (Figure 4).

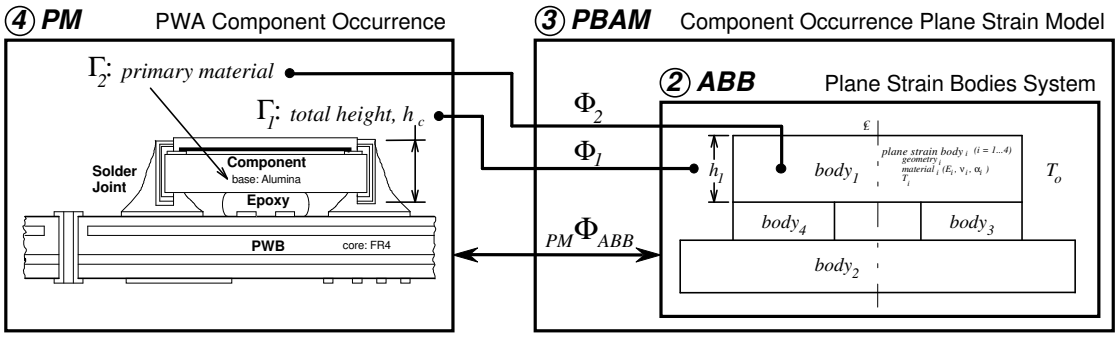


Figure 4 Design-Analysis Associativity Example

Finally, **product model-based analysis models** (③ PBAMs) represent the design-analysis associativity, ${}_{PM}\Phi_{ABB}$, between PMs and ABBs. These associativity linkages indicate the *usage* of analysis idealizations for a particular analysis application. Thus, PBAMs show how product-independent ABBs are supplied with design-related information to solve product-specific analysis problems. Figure 4 illustrates these combined concepts via a solder joint analysis example, where a surface mount resistor (a complicated component in its own right) is modeled as a homogeneous plane strain body.

Routine Analysis Automation

A major focus of the multi-representation integration architecture has been the automation of what we call **routine analysis**: *regularly using established analysis models to support product design*. In a nutshell,

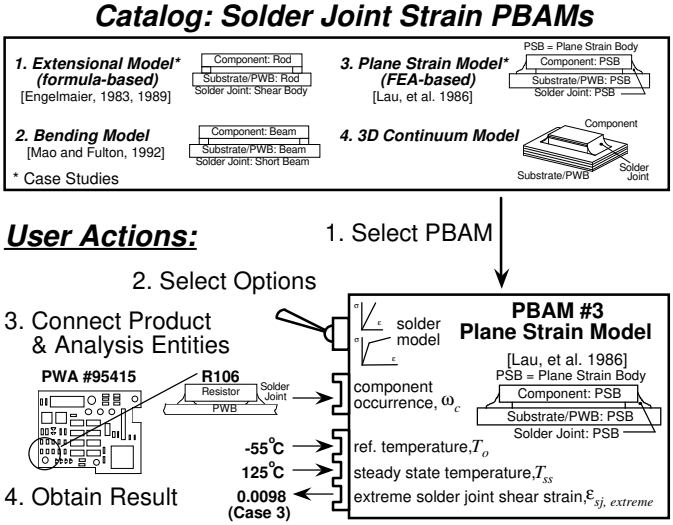


Figure 5 Routine Analysis Using PBAMs

catalogs of specialized PBAMs (Figure 5) that represent routine analysis models are first developed and implemented by an engineering analyst. After that, these PBAMs are used for routine analysis in the following typical scenario: a designer 1) selects a particular PBAM, 2) selects analysis options, 3) specifies high level objects containing product information and analysis boundary conditions, and 4) requests analysis results as outputs. Internally, the PBAM then automatically instantiates an ABB based on these inputs, and the ABB subsequently instantiates an SMM, which then runs the appropriate solution tool. The SMM retrieves the results from this analysis tool and passes them back to the ABB, which then returns them to the PBAM for usage by the designer. This scenario summarizes how PBAMs bridge the gap between design and analysis models and serve as product-specific front ends to analysis tools.

Other Potential Applications

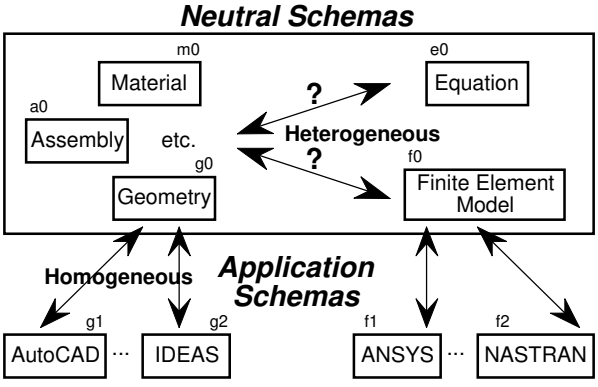
General Purpose Constraint-Object Model Notation

We developed the constraint schematic notation mentioned above primarily out of necessity as just one view of the ABB representation. However, it may be useful for other information modeling applications that could benefit from such a combination of object and constraints. One main strength of this notation is depicting relations among complex objects (analogous to electrical schematics showing connections between complex integrated circuits). This capability is achieved by graphically showing the part-of (attribute) relationship, by abstracting complex objects as subsystems (analogous to integrated circuits), and by supporting hierarchical nesting of other constraint schematics within these subsystems. [Peak and Fulton, 1993b] contains constraint schematics for solder joint analysis that illustrate these features (e.g., the Extensional Model in Figure 3-3 can be used as the Strain Model subsystem in Figure 3-2).

As developing a general purpose notation has not been the main focus of our research, it is certain that the present constraint schematic notation could be extended and benefit from input by other information modeling and constraint experts. The present notation might be a worthwhile starting point as a graphical constraint notation (analogous to EXPRESS-G) for the STEP EXPRESS information modeling language that would emphasize constraint relations.

Approach to Heterogeneous Transformation Problems

Integration efforts like STEP have mainly focused on exchanging roughly the same kind of information between different tools - what could be called **homogeneous transformations** (e.g., mapping a geometry model between formats required by design tools from Vendor A and Vendor B (Figure 6). However, some applications require transformations between two very different kinds of information - what could be called **heterogeneous transformations** (e.g., transforming the design-oriented geometric model of a part



Transformation Type	Example
Homogeneous	g1↔g0↔g2
Heterogeneous	(g0, m0, etc.)↔f0

Figure 6 The Heterogeneous Transformation Challenge

into the manufacturing-oriented geometric model of an injection molding tool that could produce the part) [Peak, 1993, p. 24]. Such transformations can also be considered the associativity between the two different types of information. Representing the transformation itself is important, e.g., so consistency can be maintained between the two types of information when changes occur.

We believe defining intermediate representations that are **associativity containers** is one approach to the heterogeneous transformation problem. In our design-analysis integration research, product model-analysis model associativity, ${}_{PM}\Phi_{ABB}$, is a heterogeneous transformation, and PBAMs are the related associativity containers. Therefore, the use of this approach in the multi-representation architecture (Figure 1) might be a helpful example for other applications involving heterogeneous transformations.

Conclusion

To date we have focused primarily on the definition of the PBAM representation and its use in routine analysis automation. PBAMs in particular and the multi-representation architecture in general have been evaluated using thermomechanical solder joint fatigue as a representative routine analysis case study. A "starter set" of ABBs and a few representative SMMs have also been developed to support this application. Results show that specialized PBAMs enable highly automated routine analysis and uniformly represent analysis models containing a mixture of both formula-based and finite element-based relations. Analysis options are also supported, for example, that allow a designer to switch easily between computationally cheaper linear models and more accurate nonlinear models (Figure 5). Furthermore, due to the multidirectional capability inherent in constraints, PBAM inputs and outputs can be reversed in some cases to support design parameter studies.

Preliminary PBAM development and implementation guidelines are available which constitute a *methodology* for automating routine analysis. Though this methodology has not yet been refined through widespread usage, we feel it is applicable to routine analysis in a wide variety of product domains. Other capabilities and limitations of PBAMs and the multi-representation architecture are discussed in the below references.

Acknowledgments

This research was initiated at Georgia Tech under the direction of Robert E. Fulton. Funding has been provided by the Georgia Tech Manufacturing Research Center (MARC) and its industrial sponsors: DEC, Ford, IBM, Motorola, and the U. S. Army Missile Command. Russell S. Peak was part of the MARC project until December, 1993, at which time he graduated and joined the Hitachi, Ltd., Mechanical Engineering Research Laboratory as a Visiting Researcher. Investigation is continuing both at Georgia Tech and Hitachi; however, these two efforts are distinct and not formally related. We gratefully acknowledge the helpful comments received from the above sponsors and our colleagues.

Primary Literature

Below is an annotated bibliography of the primary multi-representation architecture references[3] in reverse chronological order. We suggest first reviewing [Peak and Fulton, 1994] (this overview), and then the WAM '93 papers [Peak and Fulton, 1993 a & b]. If there is further interest, the thesis [Peak, 1993] can be obtained.

PWA RATs[4] *User's Guide*, Ver. 1.1 (in progress).

User's guide for PWA RATs prototype which includes thesis solder joint case study PBAMs.

PWA RATs PBAM Implementation Guide, Ver. 1.1 (in progress).

Discusses implementation of PBAMs in general and thesis case study PBAMs in particular.

Peak, R. S. and Fulton, R. E., 1994, "A Multi-Representation Approach to CAD/CAE Integration: Research Overview," in *Rapid Thermomechanical Design of Electronic Products in a Flexible Integrated Enterprise, Interim Report*, 1994, Fulton, R. E, Ume, C., et al., Prj. MS-93-03, Manufacturing Research Center, Georgia Tech, Atlanta.

Overviews the multi-representation architecture and introduces clarified terminology. Includes an annotated bibliography of the primary literature. Other potential applications of the underlying information technology are also discussed.

Peak, R. S., 1993, *Product Model-Based Analytical Models (PBAMs): A New Representation of Engineering Analysis Models*, Doctoral Thesis, Georgia Institute of Technology, Atlanta.[5]

Most complete description of the multi-representation integration approach to date. Focuses on PBAM representation and includes example application to solder joint analysis. Contains starter set of ABBs; however, does not present multi-representation architecture as clearly as Figure 1. Includes revised versions of below earlier references.

Peak, R. S. and Fulton, R. E., 1993 a & b, "Automating Routine Analysis in Electronic Packaging Using Product Model-Based Analytical Models (PBAMs); Part I: PBAM Overview; Part II: Solder Joint Fatigue Case Studies," Papers 93-WA/EEP-23 and EEP-24, ASME Winter Annual Meeting (WAM '93), New Orleans LA, USA.

Part I: Early summary of routine analysis, PBAM representation, and constraint schematic notation.

Part II: Condensed version of thesis solder joint analysis case studies. Illustrates automated routine analysis, mixed formula-based and FEA-based analysis models, multidirectional capabilities, and capabilities of constraint schematic notation.

Fulton, R. E. and Peak, R. S., Oct. 1993, "Integrating Information Technology with Engineering Design Models," *First International Symposium on Research into Artifacts*, U. Tokyo, Japan, pp. 52-60.

Mainly WAM '93 Part I with highlights from Part II and prototype CAD/CAE framework used for implementation.

Peak, R. S. and Fulton, R. E., 1992b, "Integrating Analysis and Design Information in Electronic Packaging Using Product-Based Analytical Models," *Computer Aided Design in Electronic Packaging,* ASME WAM, EEP-Vol 3, Anaheim CA, pp 41-56.

First introduction of PBAMs. Gives early EXPRESS-G models of ABB starter set. Contains a discussion of specialized PBAMs (predefined) versus general PBAMs (user-defined) not included in the thesis.

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[3] Electronic PostScript versions of some references are available via e-mail. Contact Russell Peak, peak@merl.hitachi.co.jp

[4] PWA = printed wiring assembly (a circuit board); RATs = routine analysis tools

[5] Thesis copies available from:

a. University Microfilms, Inc., P. O. Box 1346, Ann Arbor, Michigan 48106, phone: 313-761-4700

b. Georgia Tech Manufacturing Research Center (MARC), Atlanta, Georgia 30332
Reference: part of MARC Project MS-93-03
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