X-Analysis Integration Technology

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Abstract

This document overviews X-analysis integration (XAI) technology and example applications. It serves as a guide to recent research and development in this arena carried out by EIS Lab. References to in-depth descriptions of the underlying concepts and applications are included in an annotated bibliography.

1 Motivation

Linking design and analysis models is profoundly different than typical data integration tasks in that it requires *multidirectional heterogeneous transformations* - transforming one or more types of information (e.g., design geometry and materials) into a *different type* of information (e.g., an idealized finite element model) and vice-versa. Today such idealization transformations are usually not articulated in any form, much less captured as computable CAD-CAE associativity (Figure 4a), thus seriously limiting automation and knowledge capture. The integration challenge is further complicated in that a given type of product can have numerous types of analysis models that vary in discipline, resolution, application, and fidelity [Peak 1993; Peak *et al.* 1998]. We believe this diversity makes the gap between design and analysis too large for a single span integration bridge.

2 Technical Approach

2.1 MRA Conceptual Architecture

The multi-representation architecture (MRA) has been developed with intermediate representations as stepping stones to achieve the flexibility and modularity dictated by the above simulation-based engineering (SBE) needs (Figure 1). It is particularly aimed at capturing reusable analysis knowledge at the preliminary and detailed design stages.

In the MRA conceptual architecture, solution method models (SMMs) are object-oriented wrappers around detailed solution tools that obtain analysis results in a highly automated manner. They support white box reuse of existing tools (e.g., FEA tools and in-house codes) within an integrated framework (Figure 5, Figure 8). Analysis building blocks (ABBs) represent analytical engineering concepts as semantically rich objects independent of solution method and product domain. ABBs generate SMMs based on solution technique-specific considerations such as symmetry and mesh density. Analyzable product models (APMs) represent design-oriented details, providing a common stepping stone to multiple design tools and supporting multi-fidelity analysis idealizations [Tamburini, 1999]. Finally, context-based analysis models

(CBAMs) explicitly represent the fine-grained associativity between a design model and its diverse analysis models (i.e., between ABBs and APMs). CBAMs are also known as analysis modules and analysis templates.

Figure 1 illustrates these concepts via a solder joint analysis example [Peak *et al.* 1998]. Due to the coefficient of thermal expansion mismatch between the printing wiring board (PWB) and component, the solder joint deforms under thermal loads. The goal of this analysis model is to compute the resulting strain in order to estimate solder joint fatigue life. The left side shows design-related details of APM entities: the cross-section of a component, a PWB, solder joints, and epoxy. The assembly of these entities is another APM entity, a PWA component occurrence, ω_c. On the right, the ABB is a generic analysis system, *Plane Strain Bodies System*, that can be used in analyses for multiple types of products.

The CBAM, *Solder Joint Plane Strain Model*, contains associativity linkages, Φ_i, which indicate how the APM design entities are idealized as homogeneous plane strain bodies in the ABB. For example, linkage Φ_1 explicitly specifies that the height of ABB $body_1$, h_1, equals the total height of the component, h_c (a geometric idealization, Γ_1, of the detailed APM component entity). Linkage Φ_2 similarly specifies the material model for $body_1$. While the top figure shows this design-analysis associativity informally, the lower one is a constraint schematic - a structured information model that specifies all associativity linkages. As COBs, these such product-specific analysis models also have underlying lexical forms.

2.2 Constrained Objects (COBs)

Object and constraint graph techniques are combined in a new knowledge representation termed constrained objects (COBs) to represent ABBs, APMs, and CBAMs [Wilson, 2000]. COBs have the following capabilities:

- Various information modeling forms: computable lexical forms (including STEP EXPRESS) and human-interpretable graphical forms (Figure 2)
- Object constructs: sub/supertypes, inheritance, basic aggregates, and multi-fidelity objects
- Multi-directionality (I/O changes)
- Wrapping external programs as white box relations
- Adaptability, reusability, modularity, and semantics richness.

COB multi-directionality is particularly important to aid design synthesis (sizing) and design verification (analysis) within the same analysis module.

2.3 Methodology

The MRA *routinization process* (Figure 1) is a knowledge capture technique for transforming physical behavior research and design standards into catalogs of ready-to-use analysis modules [Peak *et al.* 1999a]. Working with designers, analysts identify commonly needed analyses and implement them as CBAM templates. *Routine analysis* then involves the regular usage of module instances to support product design.

3 Toolkit Implementation

XaiTools Framework™ is a second-generation Java-based prototype toolkit that implements MRA X-analysis integration concepts (Figure 1). It is targeted at design-analysis integration (Figure 3 and Figure 4) in CAD/CAE environments with high diversity (e.g., diversity of parts, analysis discipline, analysis idealization fidelity, design tools, and analysis tools) and where explicit design-analysis associativity is important (e.g., for automation, knowledge capture, and auditing).

The current tool architecture (Figure 5) supports:

- Integration with representative CORBA-based analysis tools: FEA (*Ansys*) and general math (*Mathematica*)

- Integration with representative design tools: mechanical CAD (CATIA), electrical CAD (via STEP AP210 DIS WD1.7), custom tools, and libraries (e.g., materials and fasteners)
- COB-based analysis module libraries
- Basic COB authoring tools
- Multi-directional constraint solver: COB-based wrapper for *Mathematica*

4 Applications & Benefits

Example industrial applications include PWA-B thermomechanical analysis, electronic packaging thermal resistance analysis, and aerospace structural analysis (Figure 3, Figure 4, Figure 6) [Peak *et al.* 1997, 1999c, 2000a]. Product-specific applications such as *XaiTools PWA-B*™ and *XaiTools ChipPackage*™ have been built upon this general-purpose foundation. In a nutshell product-specific CBAMs and product model entities (APMs) are added as COB subclasses. Related techniques [Koo, 2000; Zhou *et al.* 1997] intelligently leverage product model knowledge to mesh and combine building blocks into complex finite element models - models that are often impractical with brute force automeshing (Figure 4).

Distinctive benefits include greater than 10:1 reduction in analysis modeling time, highly automated parametric FEA, self-serve analysis for supply chains at Internet-based engineering service bureaus (ESBs) (Figure 7, Figure 8) [Scholand *et al.* 1999], capture of multi-fidelity multi-directional reusable analysis knowledge, and standards-based product data-driven analysis. Overall the MRA approach has divided the CAD-CAE gulf into natural object-oriented packages coupled with explicit associativity to fundamentally address the integration issues identified above.

5 Further Research

Current research includes MRA-based optimization [Cimtalay, 2000], simulation-based manufacturing [Scholand, 2000], generalized product data-driven finite element meshing, and advanced geometric idealization associativity. Other research directions include:

- Advanced constrained object constructs (e.g., higher order constraints, subgraph buffering, general aggregate relations, and time domain attributes)
- Multi-level inter-analysis associativity and related conditions and loads that originate from product requirements
- Techniques and tools for interactively constructing and using COBs in multi-user environments
- Automated pullable views combining documentation languages like XML and COB techniques (e.g., to show results summaries)

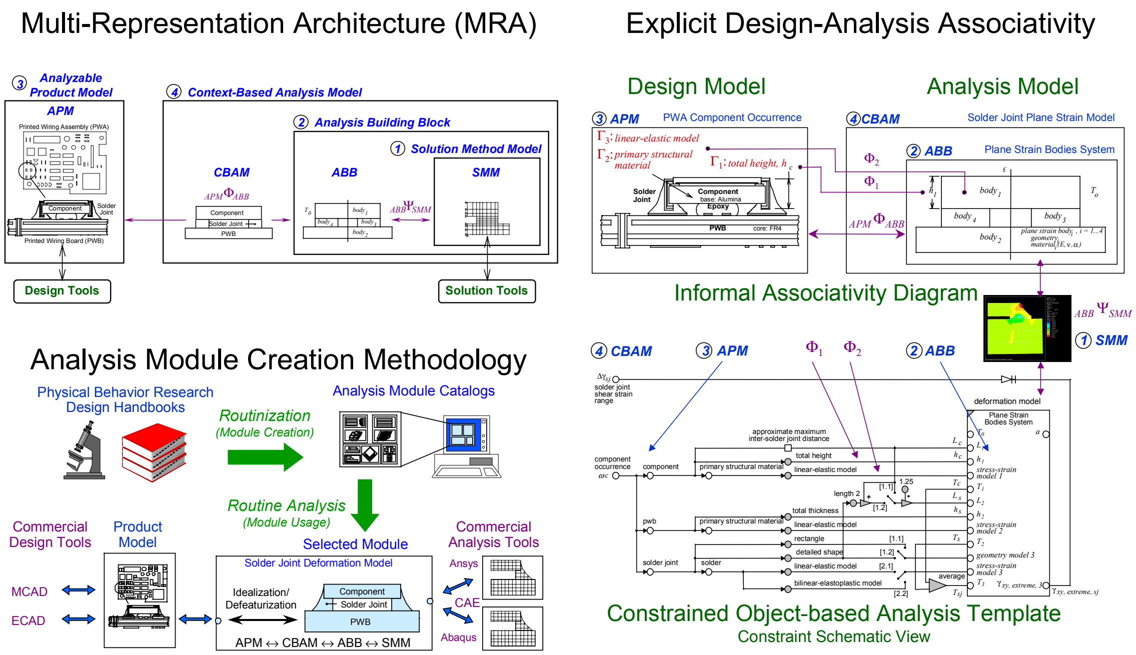
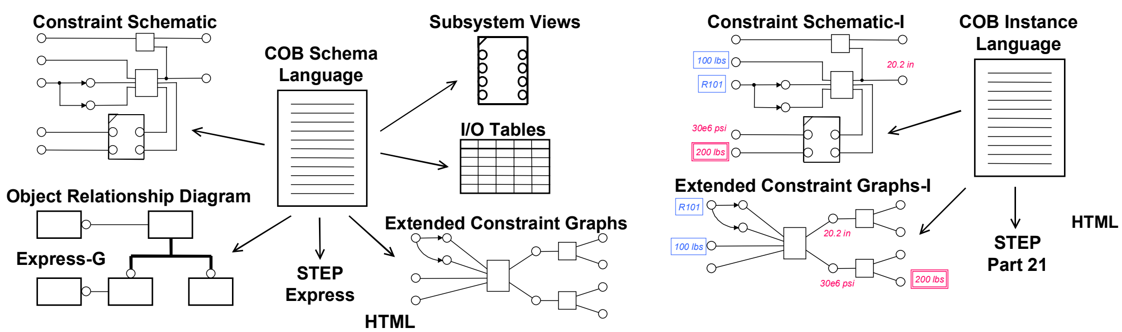


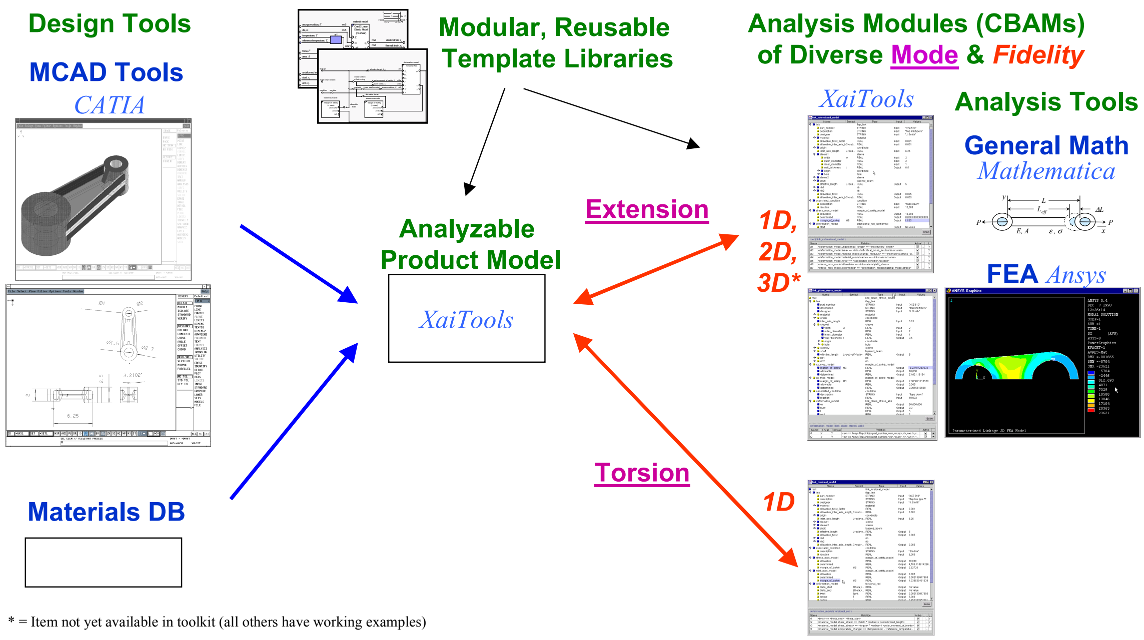
Figure 1 Recent analysis integration concepts



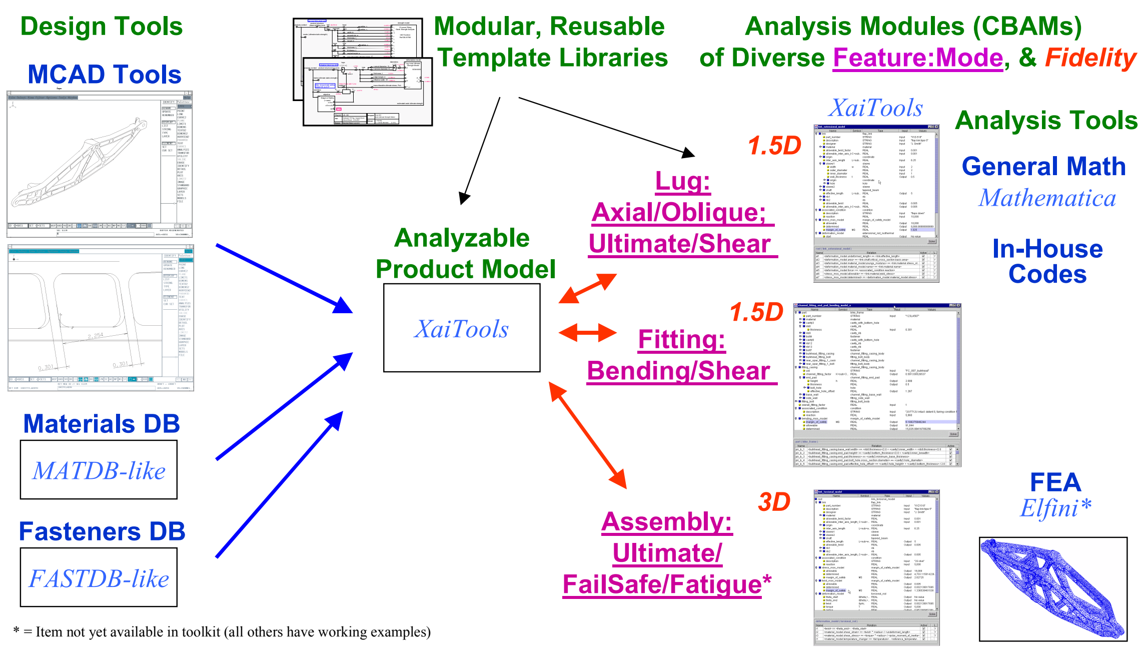
a. COB Schema (cos)

b. COB Instance (coi)

Figure 2 Lexical and graphical forms of the COB representation

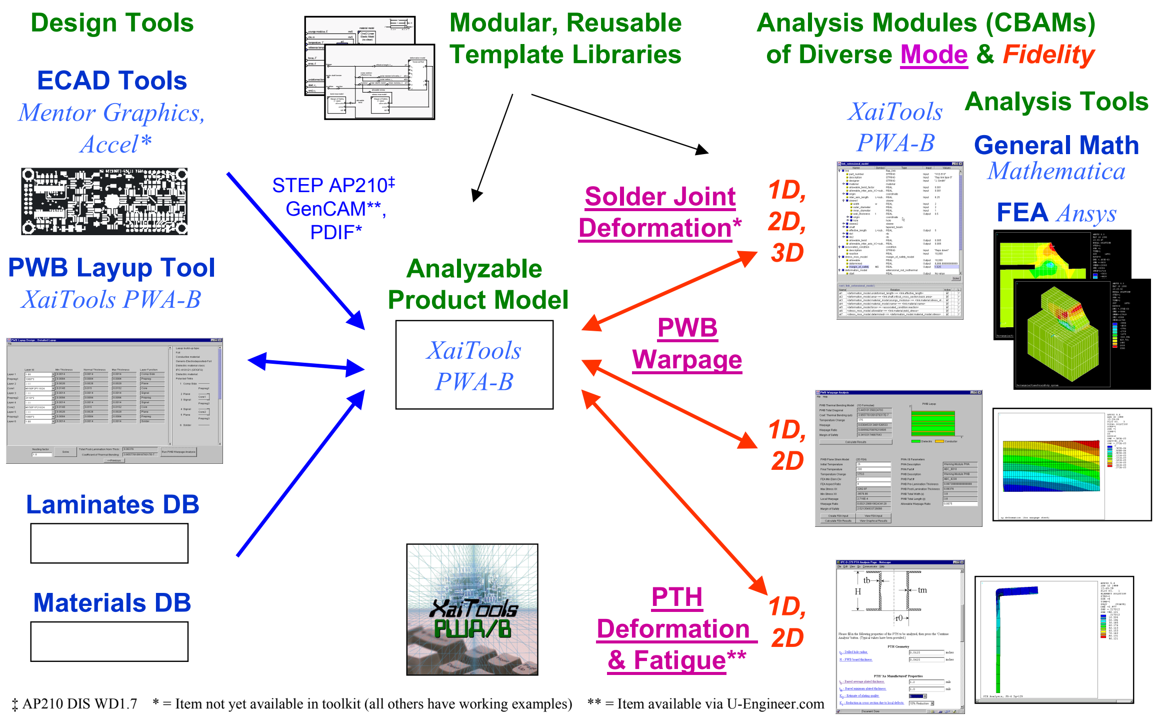


a. Tutorial examples: "flap link" mechanical part

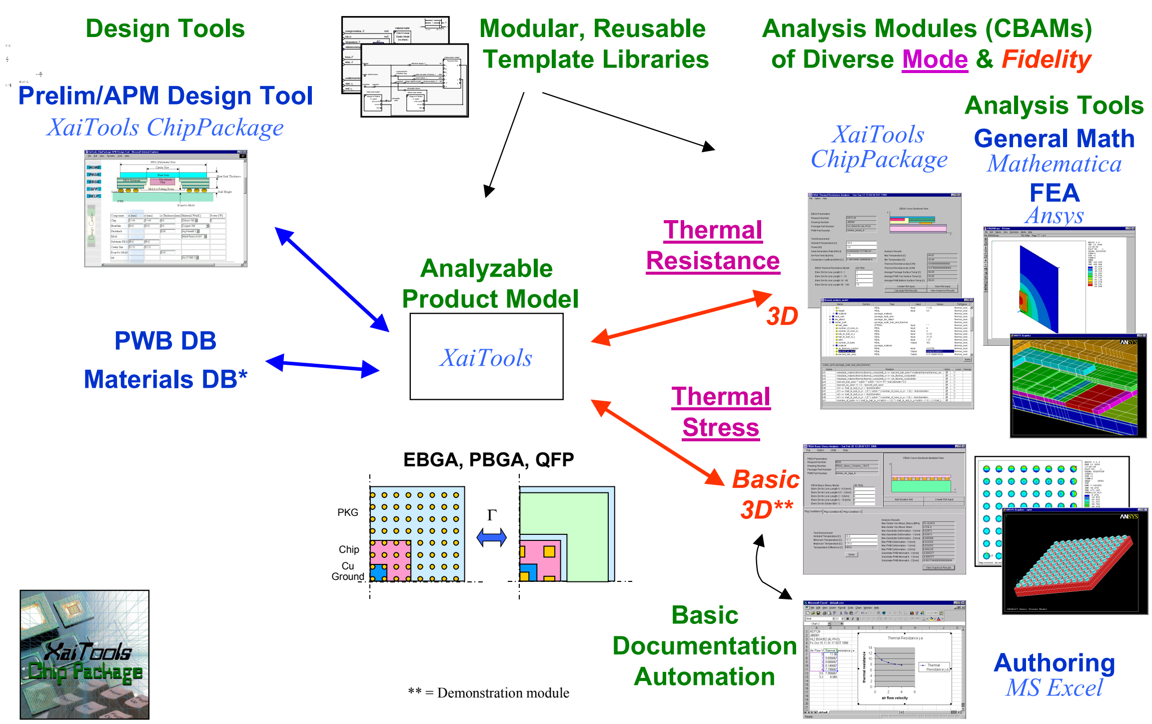


b. Aerospace examples: "bike frame" mechanical part

Figure 3 Flexible MRA design-analysis integration using COBs in *XaiTools*

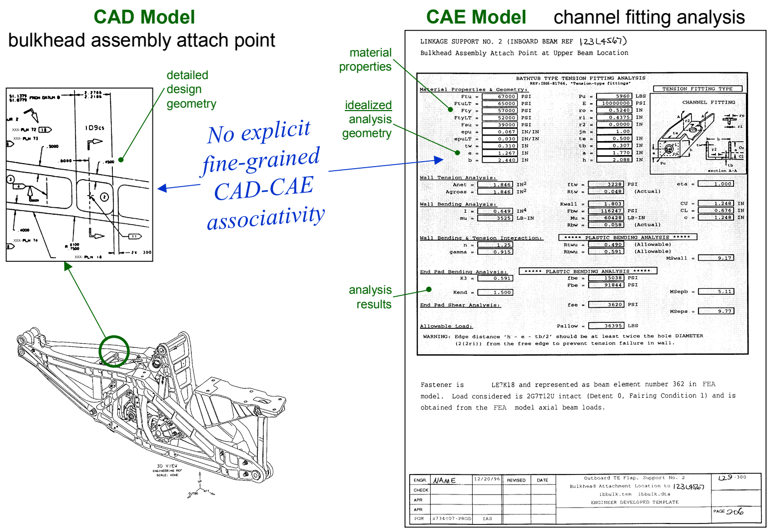


c. Electronic packaging examples: PWA/Bs

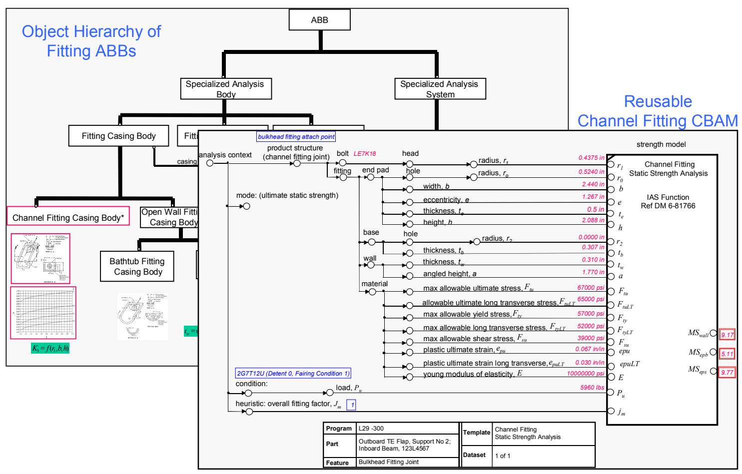


d. Electronic packaging examples: chip packages

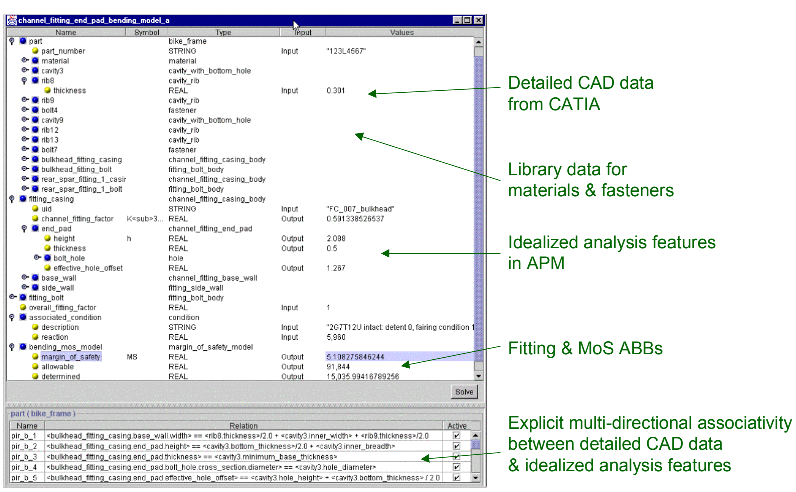
Figure 3 Flexible MRA design-analysis integration using COBs in *XaiTools* (continued)



a. Representative current practice



b. Template Representation as COBs



c. Integrated implementation in MRA-based *XaiTools*

Figure 4 Aerospace analysis modules for channel fitting analysis

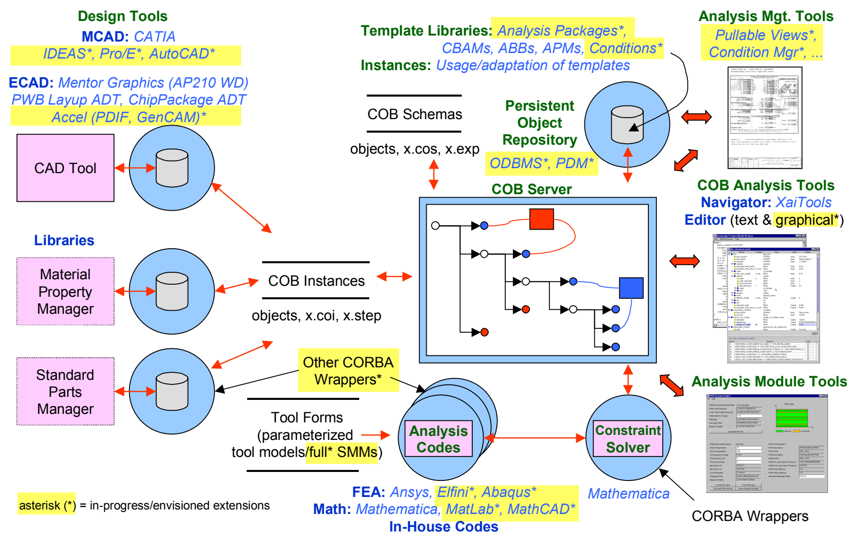
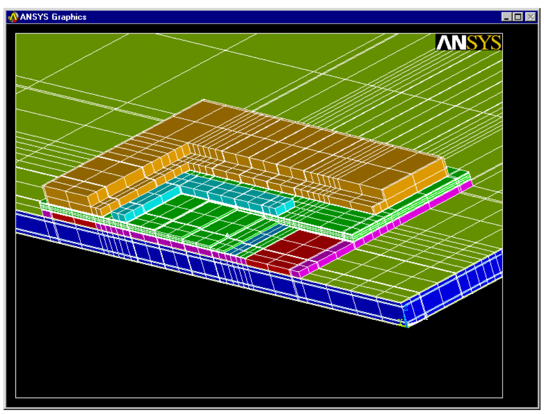
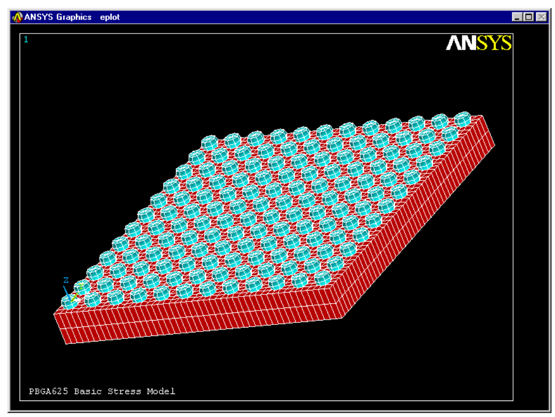


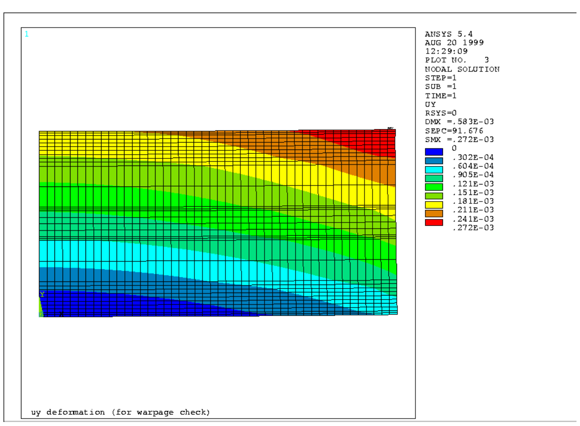
Figure 5 Product domain-independent XaiTools architecture



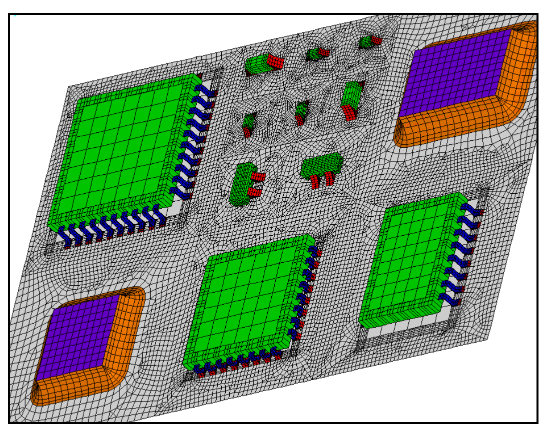
a. Ball grid array thermal resistance model
[Koo, 2000; Peak et al. 2000a]



b. Ball grid array stress model
[Zeng in Peak et al. 2000a]



c. PWB thermomechanical deformation model
[Koo, 2000; Peak et al. 1999c]



c. PWA thermomechanical deformation model
[Zhou et al. 1997]

Figure 6 Highly automated product data-driven finite element modeling

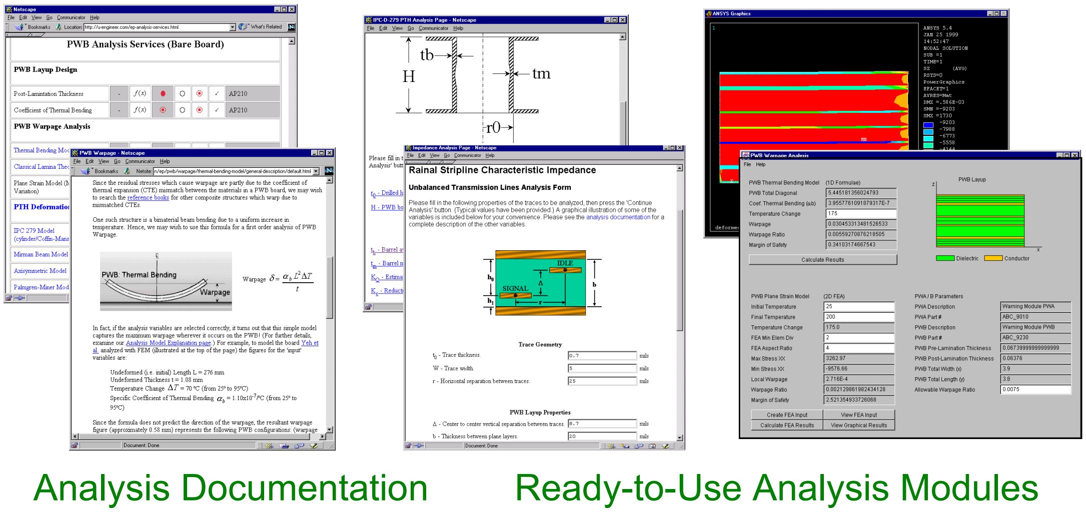


Figure 7 U-Engineer.com - An Internet-based engineering service bureau (ESB)

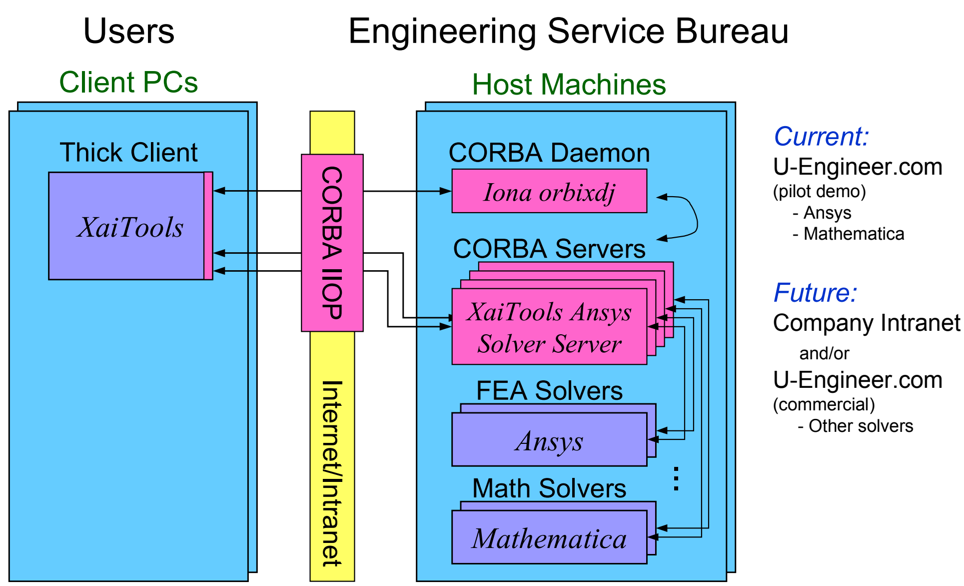


Figure 8 Automated execution of Internet/Intranet-based analysis solvers

6 Bibliography

6.1 Engineering Change Management

Cohen, T.; Navathe, S. B.; Fulton, R.E (to appear 2000) C-FAR: Change Favorable Representation, Invited Paper for Special Issue: "CAD After 2000: Integrated, Intelligent, Collaborative" *CAD Journal*.

Cohen, T.; Peak, R.S.; Fulton, R.E. (Sept. 1999) Evaluating A Change Process Product Data Model For An Analysis Driven Supply Chain Case Study, 1999 ASME Design Engineering Technical Conferences, Proceedings of DETC99, Las Vegas, Nevada, 9014.

Cohen, T.; Fulton, R.E. (1998) A Data Approach to Tracking and Evaluating Engineering Changes, 1998 ASME Design Engineering Technical Conferences, Proceedings of DETC'98, Atlanta.

Cohen, T. (1997) *A Data Approach to Tracking and Evaluating Engineering Changes*, Doctoral Thesis, Georgia Institute of Technology, Atlanta.

6.2 Analysis Integration

The following papers overview recent X-analysis integration (XAI) research and applications (including electronic packaging thermomechanical analysis and aerospace structural analysis). Most publications are accessible on the web at *http://eislab.gatech.edu/* along with other research, project, and toolkit information.

Other publications are planned describing newer developments (e.g., CBAMs) and applications (e.g., thermal resistance analysis for electronic chip packages). Advances beyond the main MRA paper [Peak *et al.* 1998] include:

- *APMs* – Combine & filter design information from multiple sources and add idealizations that are reusable in potentially many analyses (typically in CBAMs) [Tamburini, 1999]. Recognizes that the full design-oriented PM is not typically required for analysis, thus simplifying APM management.
- *CBAMs (context-based analysis models)* – Generalizes PBAMs by adding associativity with the context of why an analysis is being done, including objectives (e.g., determining margin of safety). PBAMs focused on associativity between design objects (APM entities) and product-independent analysis objects (ABBs). Other context elements under development include the requirements and behavior modes being analyzed and boundary condition objects (loads, conditions, and links to next-higher analyses).
- *Lexical COBs* – Generalizes the 'ABB structure' as the primary computable lexical representation for constraint graphs underlying APMs, ABBs, and CBAMs [Wilson, 2000].
- *Mechanical/aerospace part applications* – Demonstrates MRA product domain independence through examples beyond earlier electronic packaging applications [Peak *et al.* 1999b]. Utilizes techniques for integrating APMs with general geometric CAD models such as CATIA models [Chandrasekhar, 1999].
- *XaiTools* – next-generation Java-based MRA toolkit (beyond Smalltalk-based *DaiTools*). Includes:
    - *Mathematica-based constraint solver* – Manages basic associativity relations (typically equalities) as well as complex idealization and analysis relations. Viewed as a key step towards a subsolver architecture in which solution tools like *Mathematica* would be SMM-based subsolvers.
    - *CORBA-based wrappers* - Next-generation means for multi-platform distributed computing (e.g., it is now used to wrap *Mathematica* as the main shared constraint solver and Ansys for FEA analysis; other anticipated applications include other SMMs, design tools, and persistent data storage).

The Multi-Representation Architecture (MRA) Technique

Peak, R. S.; Scholand, A. J.; Tamburini D. R.; Fulton, R. E. (1999a) 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, 1-15.

Overviews the routinization methodology for creating highly automated product data-driven analysis modules that can be implemented in the MRA (c. 1997).

Peak, R. S.; Fulton, R. E.; Nishigaki, I.; Okamoto, N. (1998) Integrating Engineering Design and Analysis Using a Multi- Representation Approach. *Engineering with Computers*, Vol. 14 No. 2, 93-114.

Introduces the multi-representation architecture (MRA) which places product models (PMs), PBAMs, ABBs, and solution method models (SMMs) in a broader, interdependent context. Presents the explicit representation of design-analysis associativity, and proposes a routine analysis automation methodology (c. 1995). APMs, CBAMs, and lexical COBs are newer MRA concepts described elsewhere.

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

Focuses on the PBAM representation (including the ABB representation and constraint schematics) and automation of routine analysis. Includes example applications to solder joint analysis, and defines objectives for analysis model representations. Contains a starter set of ABBs. Discusses PMs and a precursor to SMMs, but does not explicitly define the MRA itself.

Constrained Objects (COBs)

Wilson, M. W. (expected 2000), *The Constrained Object (COB) Representation for Engineering Analysis Integration*, Masters Thesis, Georgia Institute of Technology, Atlanta.

Defines the primary computable lexical representation for the constraint graph-based objects underlying APMs, ABBs, and CBAMs.

Analyzable Product Models (APMs)

Tamburini, D. R (1999), *The Analyzable Product Model Representation to Support Design-Analysis Integration*, Doctoral Thesis, Georgia Institute of Technology, Atlanta.

Introduces the analyzable product model (APM) as a product model representation specifically for engineering analysis. APMs coordinate design data from multiple sources (including STEP models) and add multi-fidelity idealizations to support diverse analysis models.

Tamburini, D. R., Peak, R. S., Fulton R. E. (1997) Driving PWA Thermomechanical Analysis from STEP AP210 Product Models, *CAE/CAD and Thermal Management Issues in Electronic Systems*, EEP-Vol. 23/HTD-Vol. 356, Agonafer, D., et al., eds., ASME Intl. Mech. Engr. Congress & Expo., Dallas, 33-45.

Includes slides overviewing how APM technique was used with STEP AP210 in TIGER.

Tamburini, D. R.; Peak, R. S.; Fulton, R. E. (1996) Populating Product Data for Engineering Analysis with Applications to Printed Wiring Assemblies. Application of CAE/CAD to Electronic Systems, EEP-Vol.18, Agonafer, D., et al., eds., 1996 ASME Intl. Mech. Engr. Congress & Expo., Atlanta, 33-46.

Describes how to populate APMs from design tool data via STEP. This technique was later used in TIGER [Peak et al. 1997] to drive analyses from STEP AP210 PWA product models.

Chandrasekhar, A. (1999), *Interfacing Geometric Design Models to Analyzable Product Models with Multifidelity and Mismatched Analysis Geometry*, Masters Thesis, Georgia Institute of Technology, Atlanta.

Solution Method Models (SMMs)

Koo, D.; Peak, R. S.; Fulton, R. E. (Sept. 1999) An Object-Oriented Parser-based Finite Element Analysis Tool Interface, SPIE Conference on Intelligent Systems in Design and Mfg. II, Boston, SPIE Vol. 3833, pp. 121-132.

Parametric Modular Finite Element Modeling

Koo, D. (expected 2000), Automating Highly Coupled Multi-Body Finite Element Modeling, Masters Thesis, Georgia Institute of Technology, Atlanta.

Hsiung, C. H. (expected 2000) The Reusable Engineering Analysis Preprocessing Methodology to Support Design-Analysis Integration, Doctoral Thesis, Georgia Institute of Technology, Atlanta.

Zhou, W. X. (1997), Modularized & Parametric Modeling Methodology for Concurrent Mechanical Design of Electronic Packaging, Doctoral Thesis, Georgia Institute of Technology, Atlanta.

Defines technique for taking advantage of product-specific knowledge to create complex finite element models that are not practical with typical automeshing methods.

Zhou, W. X.; Hsiung, C. H.; Fulton, R. E.; Yin, X. F.; Yeh, C. P.; Wyatt, K. (1997) CAD-Based Analysis Tools for Electronic Packaging Design (A New Modeling Methodology for a Virtual Development Environment). InterPACK'97, Kohala Coast, Hawaii.

Overview of [Zhou, 1997] as well as interactive finite element models.

Optimization

Cimtalay, S. (expected 2000), *Optimization Model Enhancement Paradigm (OMEP)*, Doctoral Thesis, Georgia Institute of Technology, Atlanta.

Cimtalay, S.; Peak, R. S.; Fulton, R. E. (1996) 'Optimization of Solder Joint Fatigue Life Using Product Model-Based Analysis Models', *Application of CAE/CAD to Electronic Systems*, EEP-Vol. 18, Agonafer, D., et al., eds., 1996 ASME Intl. Mech. Engr. Congress & Expo., Atlanta, pp. 47-53.

Internet-based Engineering Service Bureau Concepts

McLay, M.; Scholand, A. J.; Fulton, R. E. (Dec. 1999) Issues in Mapping GenCAM to XML. Markup Technologies '99, Graphic Communications Association, Philadelphia, PA.

A. J. Scholand and R. S. Peak (Aug 20, 1999) Internet-based Engineering Service Bureau (ESB) Technology, Georgia Tech Engineering Information Systems Lab Technical Report EL003-1999A.

Overviews the extended Internet-based engineering service bureau (ESB) concepts based on DoD supply chain experiences in ProAM

Scholand, A.J.; Peak, R. S.; Fulton, R. E. (Sept. 1999) Enabling Distributed Data Processing for Internet Analysis with GenX, ASME Design Engineering Technical Conference (DETC'99), Las Vegas.

Scholand, A. J.; Peak, R. S.; Fulton, R. E. (1997) The Engineering Service Bureau - Empowering SMEs to Improve Collaboratively Developed Products. CALS Expo USA, Orlando, Track 2, Session 4.

Overviews the Internet-based engineering service bureau (ESB) paradigm initiated in the DARPA-sponsored TIGER Program. Describes services ranging from self-serve to full-serve, with a focus on highly automated product data driven analysis. Includes ESB setup and user guidelines.

Applications

R. S. Peak, M. W. Wilson, D. Koo, A. J. Scholand, S. Zeng, R. E. Fulton (expected Mar. 2000a) Design-Analysis Integration Research for Electronic Packaging. Phase I Report: Needs Assessment and Basic Techniques, Georgia Tech Engineering Information Systems Lab Technical Report E-15-658-D13, Shinko Electric.

Overviews MRA-based automation of thermal resistance analysis for electronic packages, including product-data driven variable topology FEA solutions.

Peak, R. S. (Nov 29, 1999) Integrating Product Design and Analysis Models. An Overview of ProAM: Product Data-Driven Analysis in a Missile Supply Chain. 21st Century Commerce Expo, Assoc. for Enterprise Integration (AFEI), San Diego, Track 7, Session 3.

Presentation overviewing ProAM project.

R. S. Peak, A. J. Scholand, R. E. Fulton, D. Koo, D. R. Tamburini, M. W. Wilson, S. Zeng, J. H. Roberts, P. J. Spann (Aug 23, 1999c) Product Data-Driven Analysis in a Missile Supply Chain (ProAM) Final Report, Georgia Tech Engineering Information Systems Lab Technical Report E-15-642-D05, Concurrent Technologies Corp Contract N00140-96-D-1818/0008 for US DoD JECPO.

Describes tools and techniques developed in the ProAM project. Techniques cover general analysis integration and Internet-based engineering service bureau (ESB) concepts. PWA/B applications include the *XaiTools*™ toolkit and U-Engineer.com.

R. S. Peak, R. E. Fulton, A. Chandrasekhar, S. Cimtalay, M. A. Hale, D. Koo, L. Ma, A. J. Scholand, D. R. Tamburini, M. W. Wilson (Feb. 2, 1999b) Design-Analysis Associativity Technology for PSI, Phase I Report: Pilot Demonstration of STEP-based Stress Templates Georgia Tech Project E15-647, The Boeing Company Contract W309702.

Overviews MRA applications relevant to integration of aerospace structural analysis. Includes CBAM concepts, APM links to CATIA CAD models, and *XaiTools* usage of Mathematica as a COB-based constraint solver.

Peak, R. S.; Fulton, R. E.; Sitaraman, S. K. (1997) Thermomechanical CAD/CAE Integration in the TIGER PWA Toolset. InterPACK'97, Kohala Coast, Hawaii.

Shows how MRA techniques were applied in the DARPA-sponsored TIGER Program. Includes PWA and PWB thermomechanical analyses driven by STEP AP210 product models that originated in the Mentor Graphics BoardStation layout tool.

Peak, R. S.; Fulton, R. E. (1993b) Automating Routine Analysis in Electronic Packaging Using Product Model-Based Analytical Models (PBAMs), Part II: Solder Joint Fatigue Case Studies. Paper 93-WA/EEP-24, ASME Winter Annual Meeting, New Orleans.

Condensed version of solder joint analysis case studies in [Peak, 1993]. Illustrates automated routine analysis, mixed formula-based and FEA-based analysis models, multidirectional analysis, and capabilities of constraint schematic notation.

Tools

XaiTools Users Guide (1999)

XaiTools™ is Java-based toolkit for X-analysis integration based on the MRA. This document gives basic usage instructions. Other documents describing the general architecture, examples, tutorials, COB creation guidelines, and developer guidelines are planned. See the *XaiTools* home page at *http://eislab.gatech.edu/tools/XaiTools/*

XaiTools Installation and Configuration Guide (1999)

XaiTools PWA-B Users Guide (1999)

XaiTools PWA-B™ provides a PWB layup design tool and PWB warpage analysis modules to help designers and fabricators automate tedious tasks and compare design alternatives. Built upon the general-purpose *XaiTools* foundation, it can be configured as a thick client to take advantage of Internet-based analysis solvers.

XaiTools ChipPackage Users Guide (expected 2000)

U-Engineer.com (1999)

An Internet-based engineering service bureau with self-serve analysis modules for PWA designers and PWB fabricators.