Design-Analysis Associativity Technology for PSI

Phase I Report:
Pilot Demonstration of STEP-based Stress Templates

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Sponsor:
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Abstract

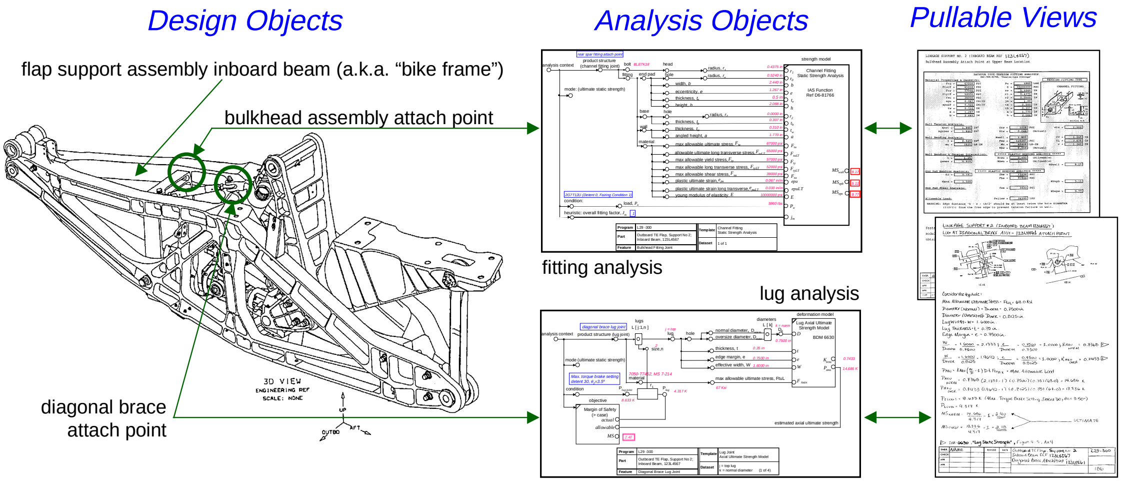
The Product Simulation Integration (PSI) Structures project is under way in Boeing Commercial Aircraft Group (BCAG) to reduce costs and cycle time in the design, analysis, and support of commercial airplanes. The objective of the PSI project is to define and enhance the processes, methods, and tools to integrate structural product simulation with structural product definition. This includes automated engineering analysis as an integral component of the product definition. Subprojects have been defined and working selected topics toward accomplishing the objectives of the PSI for BCAG Structures. Formalized integration activities have also been identified to support the PSI subprojects through their technology life cycle. [Prather & Amador, 1997]

As part of PSI, Georgia Tech has contributed an information modeling language, termed constrained objects (COBs), that is aimed at next-generation stress analysis tools. COBs combine object and constraint graph techniques to represent engineering concepts in a flexible, modular manner. COBs form the basis of the extended multi-representation architecture (MRA) for analysis integration, which is targeted at environments with high diversity in parts, analyses, and tools [Peak *et al.* 1998]. A key MRA distinctive is the support for explicit design-analysis associativity (for automation and knowledge capture) and multidirectional relations (for both design sizing and design checking). Another MRA characteristic is using COBs to represent and manage complex constraint networks that naturally underlie engineering design analysis.

Using a case study approach, lug and fitting design guides have been recast as example reusable COB libraries. The use of these and other COBs on structural parts relevant to the aerospace industry has been demonstrated. These case studies utilize *XaiTools*, a toolkit implementation of MRA concepts, which interfaces representative design tools (CATIA CAD, materials and fasteners libraries) and general purpose analysis tools (Mathematica solver, ANSYS FEA).

It is anticipated that COBs and the MRA will contribute key technologies to the overall PSI next-generation analysis tool architecture. The potential impact of explicit design-analysis associativity is significant. Capturing such knowledge, which is largely lost today, enables libraries of highly automated analysis modules and provides a precise reusable record of idealization decisions. User adaptation/creation of existing/new analysis templates is also possible.

Today creating views of analysis results such as internal analysis documentation (strength check notes) and regulatory agency summaries typically requires extensive manual effort. While COBs focus on core associativity and analysis computation relations, their combination with technology like XML should enable interactive "pullable views" to help streamline this analysis task. Other COB applications are anticipated, including upstream sizing and inter-analysis associativity.



Modular, Integrated, Active, Multidirectional,
Reusable, User-Definable

1 Introduction

This document overviews Phase 1 deliverables based on the original proposal and priority refinements directed by the sponsor. These items have been demonstrated at Boeing PSI workshops and documented in workshop minutes. Work during this phase has focused on technology needed for next generation tools as opposed to immediate improvements to current production tools.

2 Deliverables

1) **Constrained object (COB) information modeling language** for next generation integrated analysis templates.

The COB language [Wilson, 1999], based on the general purpose STEP EXPRESS information modeling language, has specific features to address the needs of engineering analysis integration. It has the following capabilities:

- *Various information modeling forms:* computable lexical forms (for automation) and graphical forms (to aid human understanding and development). (Figure 1)
- *Object constructs:* sub/supertypes, inheritance, basic aggregates, multifidelity objects
- *Multidirectionality (I/O change).* This enables both synthesis (design sizing) and verification (design checking) from the same analysis model in many cases.
- *Wrapping external programs as black box relations.* This allows use of specialty & legacy tools as appropriate within a consistent framework.

Implementing MRA concepts (below) as COBs is the main analysis application of this language.

2) **COB-based analysis integration architecture** and related methodology [Peak *et al.* 1998, 1999] (Figure 2 - Figure 3).

The extended multi-representation architecture (MRA)[1] is aimed at design-analysis integration in environments with high diversity (e.g., diversity of parts, number of analyses, analysis discipline, analysis idealization fidelity, design tools, and analysis tools) and for cases where explicit design-analysis associativity is important. It has the following main representations:

- **Analysis building blocks (ABBs)** (Figure 4-Figure 5)
  - Represent product-independent analysis concepts as reusable, modular, adaptable objects.
- **Solution method models (SMMs)** (Figure 6-Figure 7)
  - Represent tool-specific models as wrapped in semantically richer ABBs.
  - Support black box usage of existing tools (e.g., general purpose FEA and in-house codes like IAS functions, as well as tightly integrated capabilities such as CATIA GPS).
  - Fold diverse solution techniques into the constraint-based uniformity of the MRA.
- **Analyzable product models (APMs)** (Figure 8) [Tamburini, 1999]
  - Join and filter design data from multiple data sources.
  - Add multifidelity idealizations (e.g., relations between detailed CATIA geometry and idealized fitting analysis parameters) for use in possibly many analyses.
- **Context-based analysis models (CBAMs)** (Figure 9)
  - A.k.a. analysis templates, analysis modules, and analysis problems
  - Contain explicit associativity relations between design models (APMs) and analysis objects (ABBs)

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[1] See notes in the References (Section 4) for a summary of recent MRA extensions.

The PSI effort has highlighted other aspects needed in an analysis integration architecture. GIT provided initial concept development for some of these:

a) Inter-analysis associativity (between an analysis and its next-higher/peer analyses). This also deals with the representation of design requirements, conditions, and loads.
b) Pullable views that utilize COBs.

3) **CATIA CAD tagging technique** [Chandrasekhar, 1999]

This technique extracts detailed CAD model design parameters for use in analysis (Figure 10). Specifically, APMs contain relations between these design parameters and idealized analysis parameters that are used in CBAMs. We implemented and evaluated two tagging approaches in CATIA v4: geometric entity-based and dimension entity-based. The technique was tested with several CAD models including the bike frame, which has representative aerospace part complexity. The latter approach appears most promising for general use, but in CATIA v4 it is limited to one-way extraction of design parameters. Another approach using PARAM3D has been proposed that may offer two-way capabilities.

4) **Prototype analysis integration toolkit, *XaiTools*,** with Users Guide (Attachment A) and examples.

XaiTools™ is a Java-based toolkit for X-analysis integration that is a reference implementation of MRA concepts. Earlier projects showed the Smalltalk-based first generation toolkit, *DaiTools*, in action in electronic packaging environments [Peak *et al.* 1997]. Projects are underway to migrate and extend these product-data driven analysis capabilities in *XaiTools*.

Demonstrating architecture applicability across product domains, a *XaiTools* architecture for aerospace-oriented environments is summarized in Figure 11. It has the following characteristics:

- Integration with representative analysis tools:
  a) *FEA tools:* ANSYS
  b) *Symbolic solver/general math tool:* Mathematica
  c) *Other solution tools:* Via black box wrapping approach
- Integration with representative design tools:
  d) *Geometric modeling tool:* CATIA
  e) *Materials database:* MATDB-like format
  f) *Fasteners database:* FASTDB-like format
  g) *Other design tools*: via native COB instance format or STEP Part 21
- COB-based analysis template libraries with various forms[2]
- COB editing and navigation/browsing tools
- Usage of *Mathematica* as the main CORBA-wrapped constraint solver

Tools of other types and vendors can be added in a similar manner [Peak *et al.* 1997, 1998].

5) **Working development test cases & tutorial examples** demonstrating the above capabilities via formula- and FEA-based analyses:

a) Back plate
b) Flap link (Figure 12-Figure 17) – This illustrates key CBAM/MRA characteristics, including usage of library ABBs, associativity with an APM (and CAD links), multifidelity analyses, multi-mode analyses, and black box wrapping of a general purpose external tool.

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[2] *XaiTools* currently supports cos (cob schema) and coi (cob instance) models (as syntax v2.1 text files). It also supports reading/writing STEP Part 21 and STEP EXPRESS files, respectively, and writing HTML formatted versions. Graphical editing & interaction tools for constraint schematics are planned.

6) **Working aerospace case studies** relevant to Boeing (Figure 18):
   a) Bike frame APM-based CATIA linking (Figure 19).
   b) Reusable lug and fitting template libraries based on design guides (after BDM 6630 and D6-81766) (Figure 20-Figure 25, Figure 29-Figure 30). These were created using the MRA routinization methodology (Figure 3). We showed how such capabilities can be implemented as:
      i) COB wrappings around existing tools like IAS (black box approach), or
      ii) Decomposed COB hierarchies for improved modularity and multidirectionality.
   c) Flap support inboard beam (a.k.a. "bike frame") utilizing these templates (Figure 26-Figure 28, Figure 31).

7) **Collaboration with PSI team members** and participation in the following meetings & workshops:

June 1997 – San Diego (STEP meeting), Seattle	Feb 1998 – Seattle
Sept 1997 – Seattle	July 1998 – Seattle (via teleconference)
Oct 1997 – Stockholm (at EuroSTEP) and – Florence (STEP meeting)	Sept 1998 – Seattle
Dec 1997 – Seattle	Dec 1998 – Seattle

8) **Proposal outline for 1999 effort**

Proposed next steps are outlined in recently submitted memos and include the following thrusts:

- Extend lug & fitting COBs and related interfaces for pilot production usage.
- Develop next generation CATIA CAD idealization associativity (e.g., improved tagging via automated morphing techniques).
- Develop other needed architecture facets identified above (Figure 32):
  - Advanced pullable views by combining XML and COB techniques.
  - Inter-analysis associativity and related conditions/loads/requirements.

3 Summary

In Phase 1 GIT has delivered the constrained object (COB) information modeling language for next-generation stress analysis templates. Key advances beyond current practice include the capture of explicit design-analysis associativity (and related idealizations), increased modularity, and increased reusability. COBs form the basis for the extended multi-representation architecture (MRA) for analysis integration. The MRA focuses on associativity and computation coordination in environments with a diversity of analysis disciplines, analysis fidelity, product types, and computing tools. Another MRA distinctive is using COBs to represent and manage complex constraint networks that naturally underlie engineering design analysis.

Examples relevant to the aerospace industry have been demonstrated, including lug and fitting analyses with links to detailed design parameters in CATIA CAD models. Multifidelity analyses and COB-based CATIA-to-FEA scenarios have also been presented.

It is anticipated that this work will contribute key components to the overall next-generation analysis tool architecture. The potential impact of explicit design-analysis associativity cannot be overemphasized, as the traceability of this idealization knowledge is largely lost today.

Future work has been proposed to field test lug and fitting analysis capabilities based on an MRA subset of the overall PSI architecture. Other proposed thrusts include capturing inter-analysis associativity, and combining XML and COB techniques to enable advanced pullable views.

4 References

4.1 Boeing PSI Project

H. Martin Prather, Jr. and Raymond A. Amador (Nov. 17, 1997) Product Simulation Integration for Structures. 1997 MacNeal-Schwendler Corp. Aerospace Users Conference, New Port Beach CA,

Overviews Boeing Product Simulation Integration project (PSI).

4.2 GIT Analysis Integration

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

Other publications are planned describing newer developments (e.g., CBAMs) and applications (e.g., aerospace structural analysis). Advances beyond the main MRA paper [Peak *et al.* 1998] and TIGER-era capabilities [Peak *et al.* 1997, 1999] include:

- *APMs* – Combine & filter design information from multiple sources and add idealizations that are reusable in potentially many analyses (typically in CBAMs). 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 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.
- *Mechanical/aerospace part applications* – Demonstrates MRA product domain independence through examples beyond earlier electronic packaging applications. 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; other anticipated applications include SMMs, design tools, and persistent data storage).

4.2.1 The Multi-Representation Architecture (MRA) Technique

Peak, R. S.; Scholand, A. J.; Tamburini D. R.; Fulton, R. E. (to appear 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.

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.

4.2.1.1 Constrained Objects (COBs)

Wilson, M. W. (expected 1999), The Constrained Object (COB) Representation for Engineering Analysis Integration , Masters Thesis, Georgia Institute of Technology, Atlanta.

4.2.1.2 Analyzable Product Model (APM)

Chandrasekhar, A. (expected 1999), Integrating APMs with Geometric CAD Models, Masters Thesis, Georgia Institute of Technology, Atlanta.

Tamburini, D. R (expected 1999), The Analyzable Product Model (APM) Representation , Doctoral Thesis, Georgia Institute of Technology, Atlanta.

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.

> Introduces the analyzable product model (APM) as a refined type of product model (PM) aimed specifically at supporting analysis. 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.

4.2.2 Parametric, Modular Finite Element Modeling

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.

4.2.3 Applications

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.

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.

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.

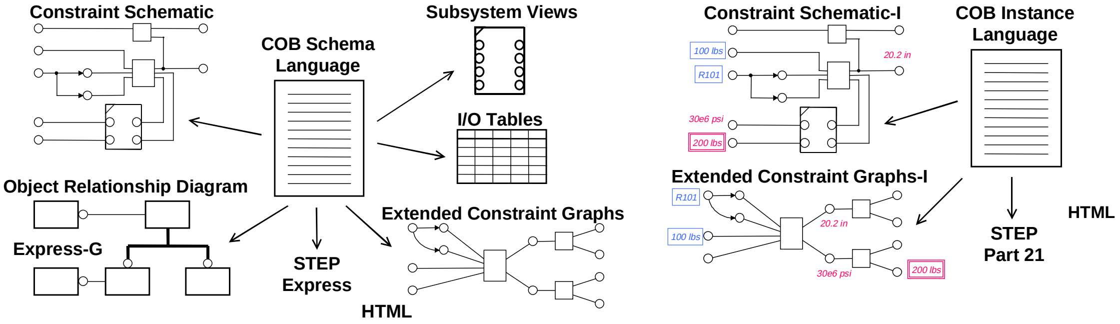
> Condensed version of solder joint analysis case studies in [Peak, 1993]. Illustrates automated routine analysis, mixed formula-based and FEA-based analysis models, multidirectional analysis, and capabilities of constraint schematic notation.

4.2.4 Tools

Wilson, M. W., Peak, R. S., Tamburini, D. R. (1999) *XaiTools Users Guide*. EIS Lab, Georgia Institute of Technology, Atlanta. *http://eislab.gatech.edu/*

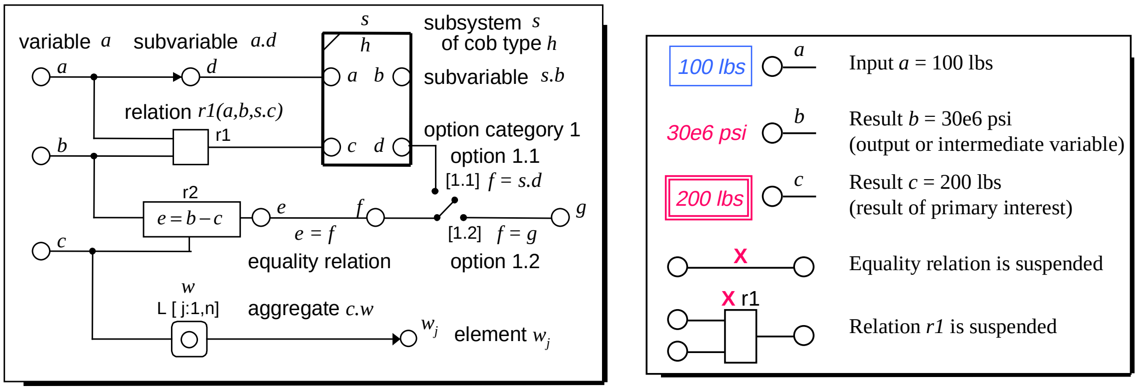
> XaiTools™ is Java-based toolkit for X-analysis integration based on the MRA. This document gives basic usage instructions. Other documents describing the general architecture, examples, tutorials, COB creation guidelines, and developer guidelines are planned.

5 Figures



a. COB Schema (cos) Forms

b. COB Instance (coi) Forms



i. COB Schema

ii. COB Instance Additions

c. Basic Constraint Schematic Notation

Figure 1 Lexical and Graphical Forms of the Constrained Object (COB) Representation

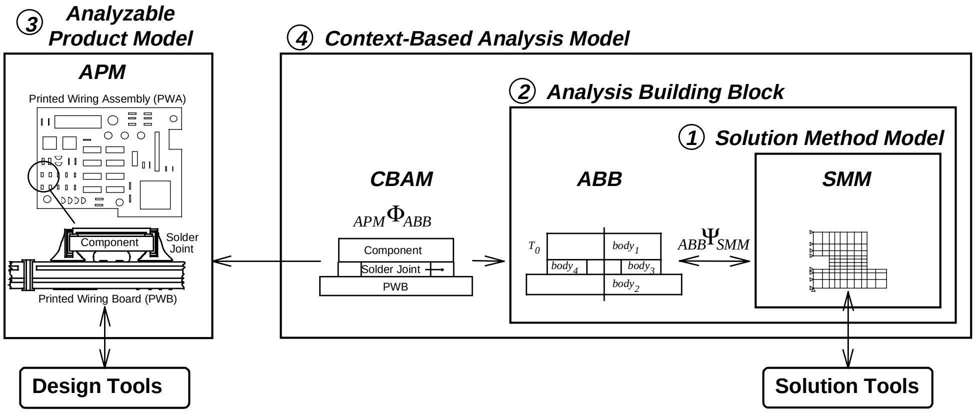


Figure 2 Extended Multi-Representation Architecture (MRA) for Analysis Integration [after Peak *et al.* 1998]

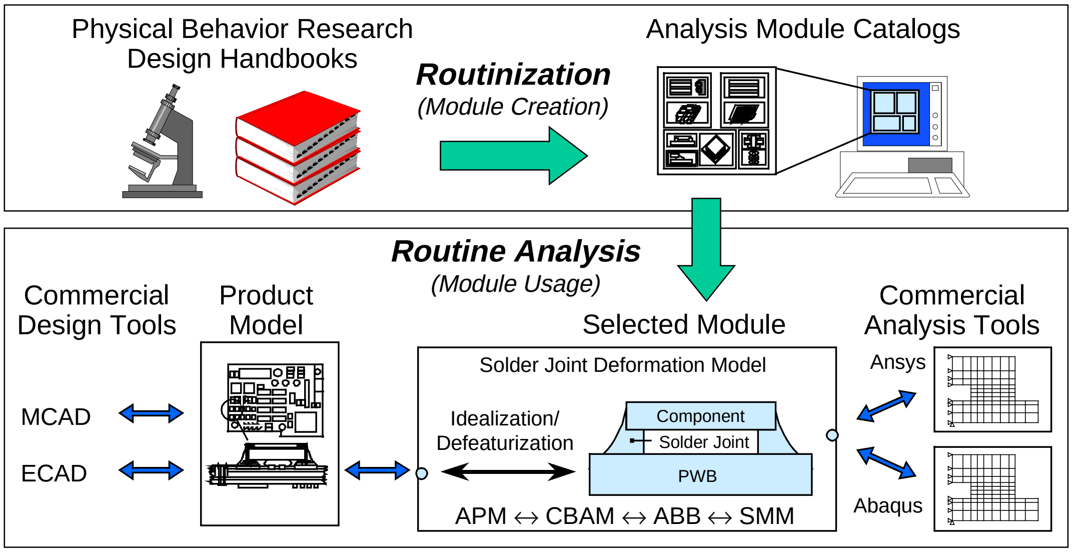


Figure 3 MRA Routinization Methodology [after Peak *et al.* 1999]

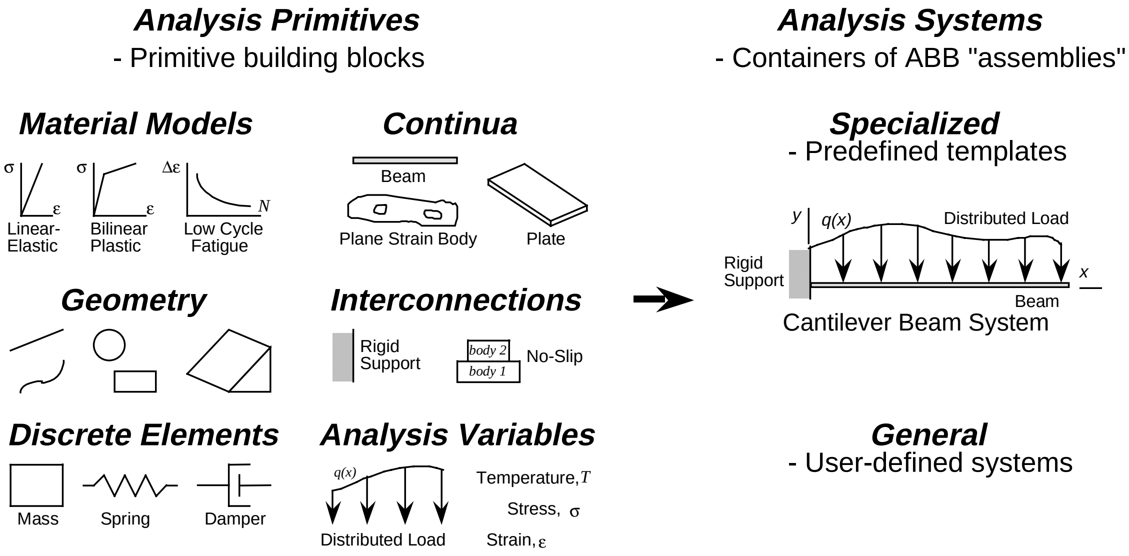


Figure 4 Categories of General Purpose ABBs

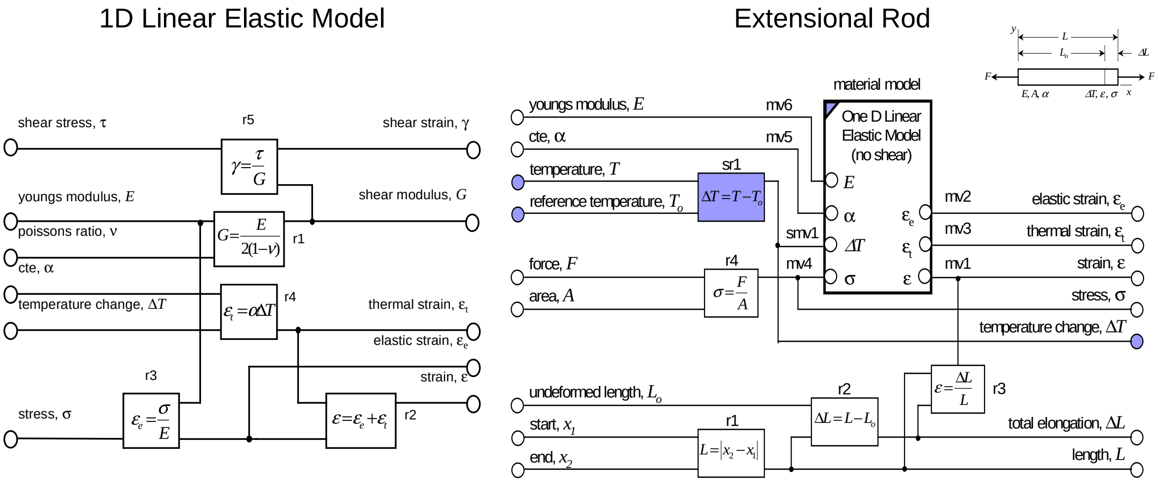
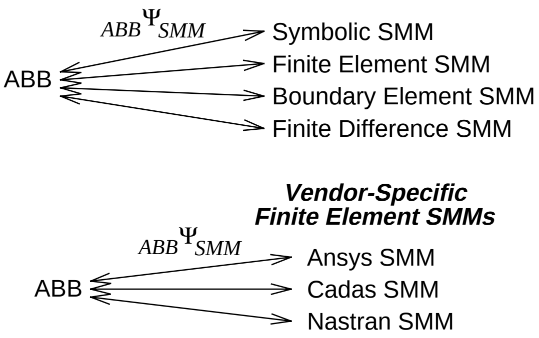
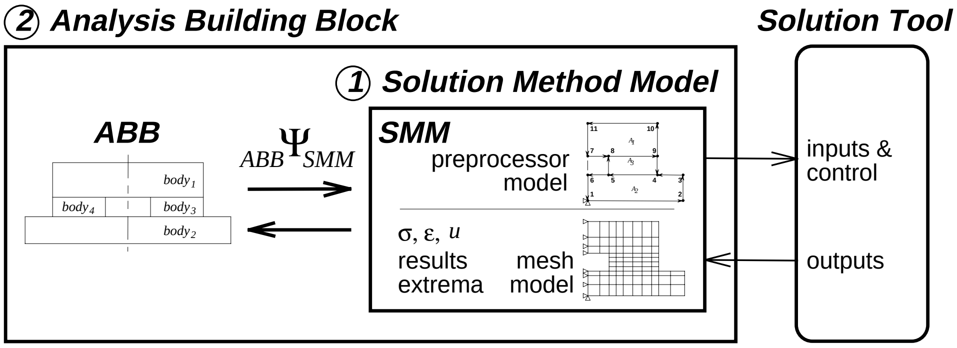


Figure 5 Example Material Model and Continuum ABBs



a. Creating SMMs of Diverse Methods and Vendors from the Same ABB



b. ABB-SMM Solution Tool Interface

Figure 6 Obtaining ABB Analysis Results via SMMs

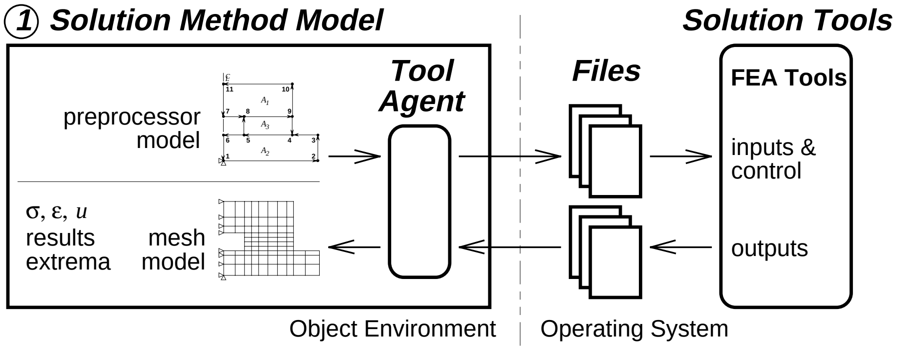
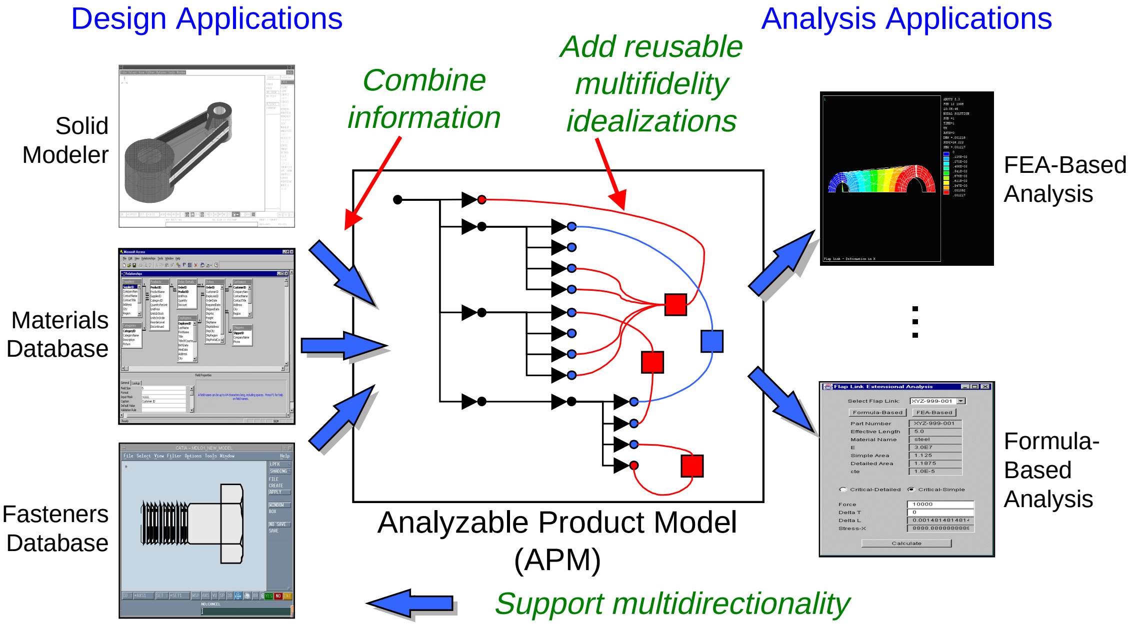


Figure 7 Automated Tool Operation via SMMs and Tool Agents



Select Flap Link: XYZ-999-001
Part Number: XYZ-999-001
Effective Length: 5.0
Material Name: steel
E: 3.0E7
Simple Area: 1.125
Detailed Area: 1.1875
cte: 1.0E-5
○ Critical-Detailed ● Critical-Simple
Force: 10000
Delta T: 0
Delta L: 0.001481481481
Stress-X: 8888.888888888

Figure 8 Analyzable Product Model (APM) Technique

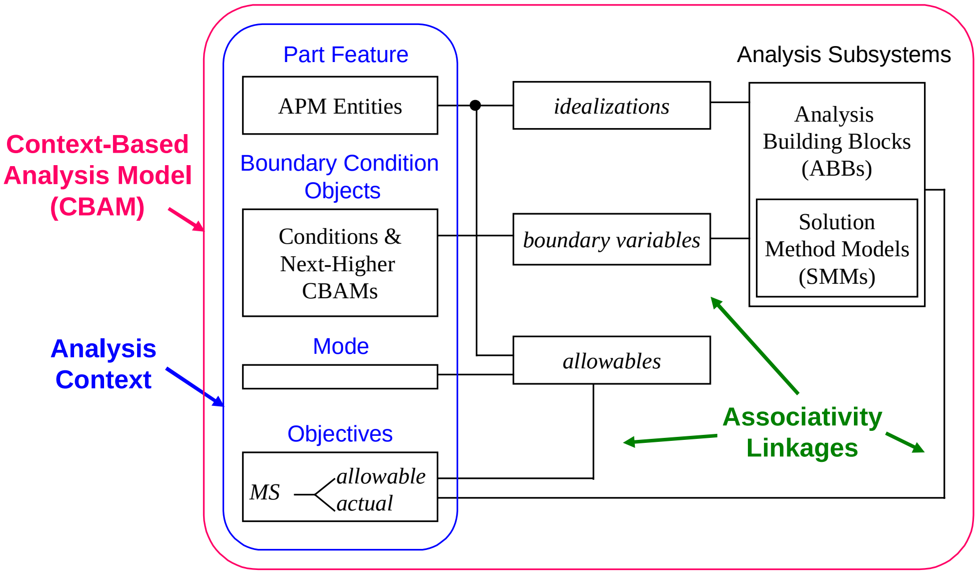
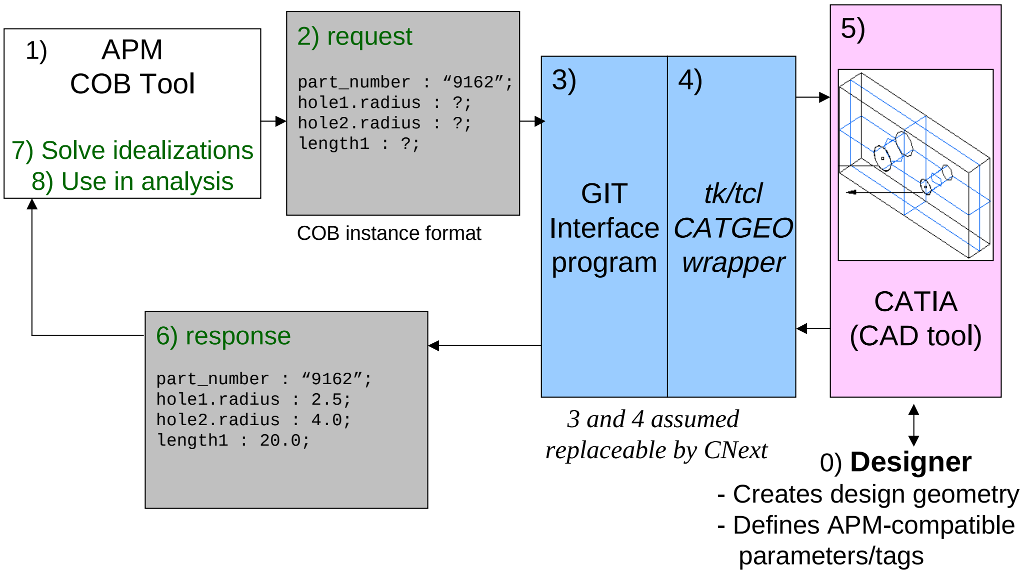


Figure 9 Structure of a Context-Based Analysis Model (CBAM)[3]



```
part_number : “9162”;
hole1.radius : ?;
hole2.radius : ?;
length1 : ?;
```

```
part_number : “9162”;
hole1.radius : 2.5;
hole2.radius : 4.0;
length1 : 20.0;
```

Figure 10 APM-based CATIA CAD Tool Interface

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[3] The boundary condition object and mode portions of CBAMs are work-in-process concepts.

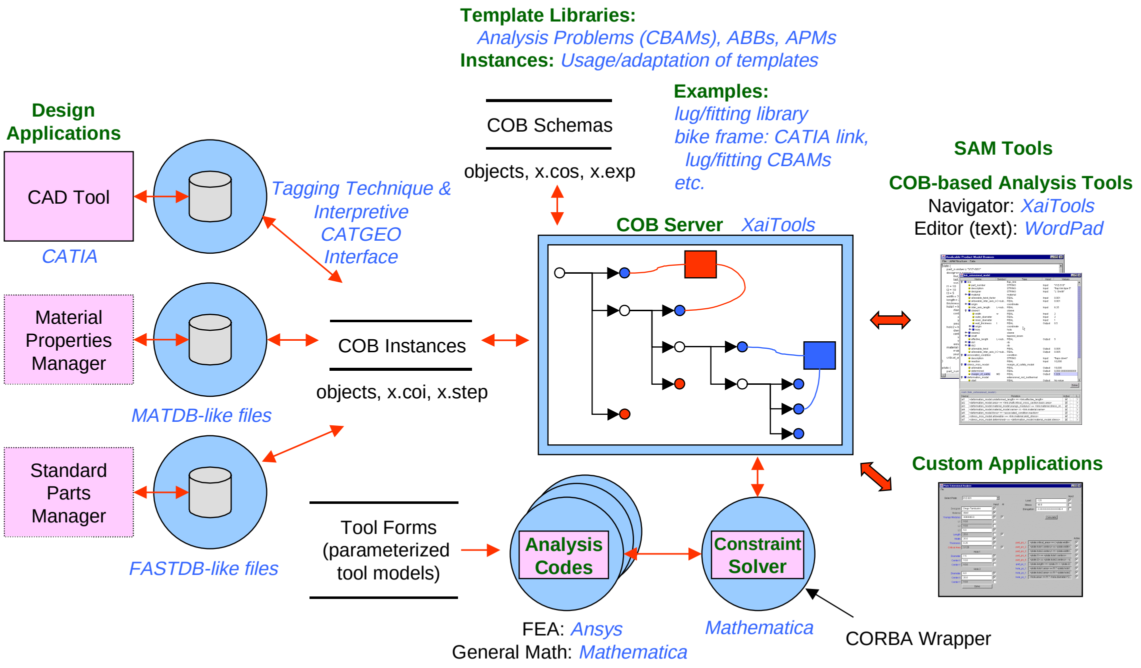

Figure 11 *XaiTools*™ Architecture for an Aerospace-Oriented Environment
(working state of current prototype; subset of needed architecture)

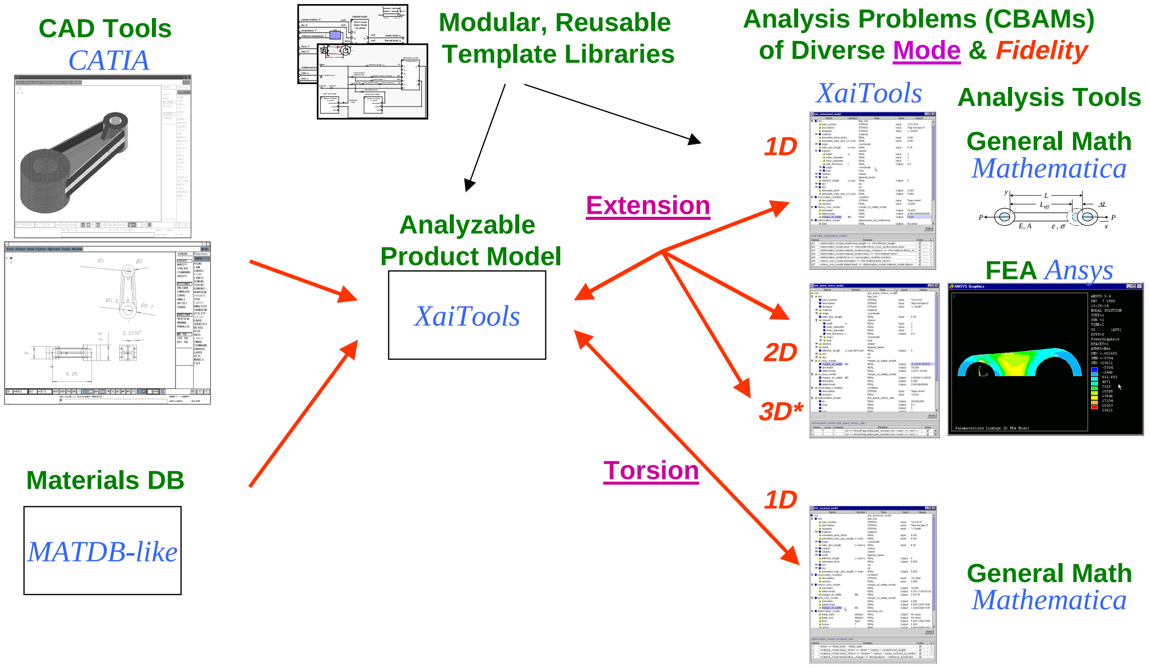

Figure 12 Flexible Design-Analysis Integration Using MRA COBs: Tutorial Example "flap link" [4]:

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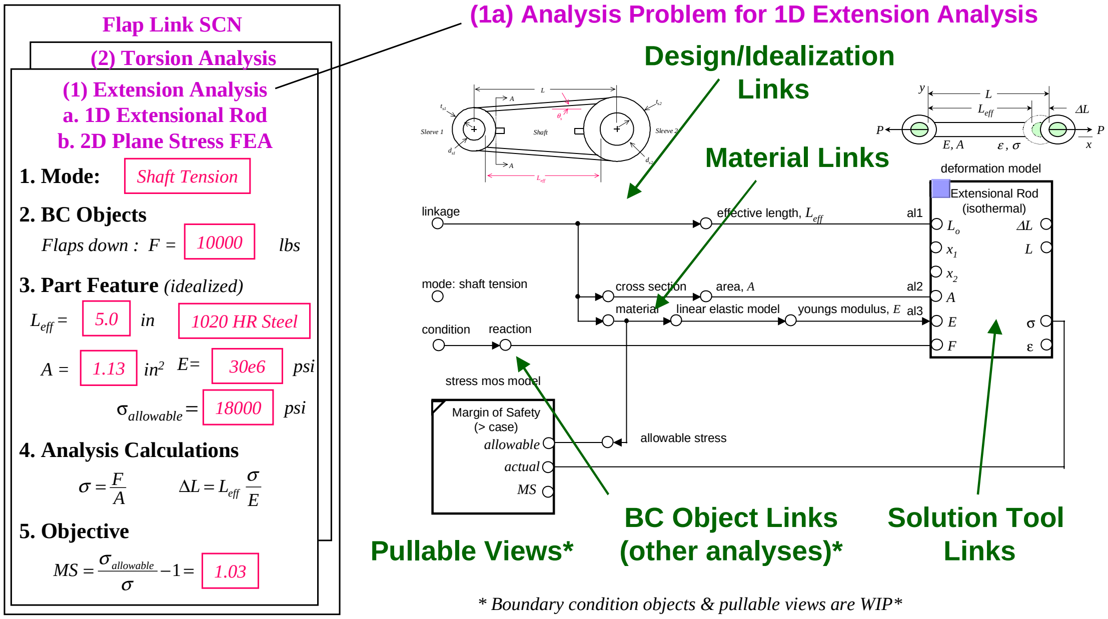
[4] Asterisks (*) indicate items not available as working prototype examples (all others are working examples)



** Boundary condition objects & pullable views are WIP**

Figure 13 Representing a Flap Link Analysis as a CBAM: Linkage Extensional Model

```
COB link_extensional_model SUBTYPE_OF link_analysis_model;
  DESCRIPTION
    "Represents 1D formula-based extensional model.";
  ANALYSIS_CONTEXT
    PART_FEATURE
     link : flap_link
    BOUNDARY_CONDITION_OBJECTS
     associated_condition : condition;
    MODE
     "tension";
    OBJECTIVES
     stress_mos_model : margin_of_safety_model;
  ANALYSIS_SUBSYSTEMS */
    deformation_model : extensional_rod_isothermal;
 RELATIONS
   al1 : "<deformation_model.undeformed_length> == <link.effective_length>";
   al2 : "<deformation_model.area> == <link.shaft.critical_cross_section.basic.area>";
   al3 : "<deformation_model.material_model.youngs_modulus> ==
            <link.material.stress_strain_model.linear_elastic.youngs_modulus>";

   al4 : "<deformation_model.material_model.name> == <link.material.name>";
   al5 : "<deformation_model.force> == <associated_condition.reaction>";

   al6 : "<stress_mos_model.allowable> == <link.material.yield_stress>";
   al7 : "<stress_mos_model.determined> == <deformation_model.material_model.stress>";
END_COB;
```

Desired categorization of attributes is shown above (as manually inserted) to support pullable views.
Categorization capabilities is a planned XaiTools extension.

Figure 14 COB Lexical Form for Linkage Extensional Model CBAM

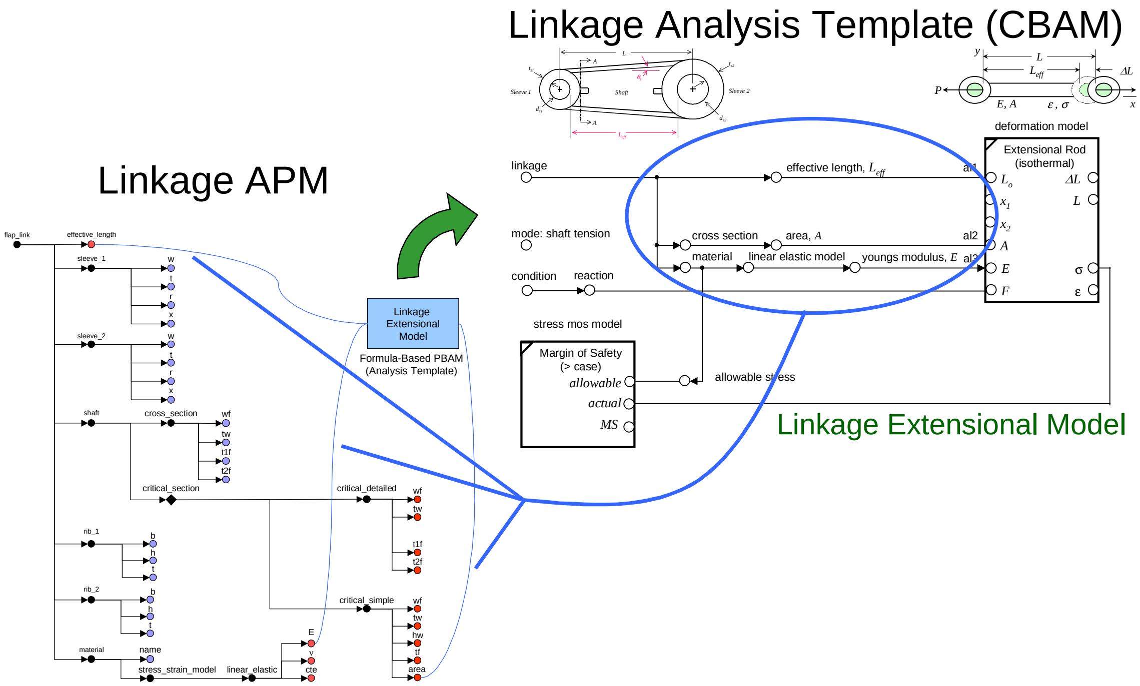
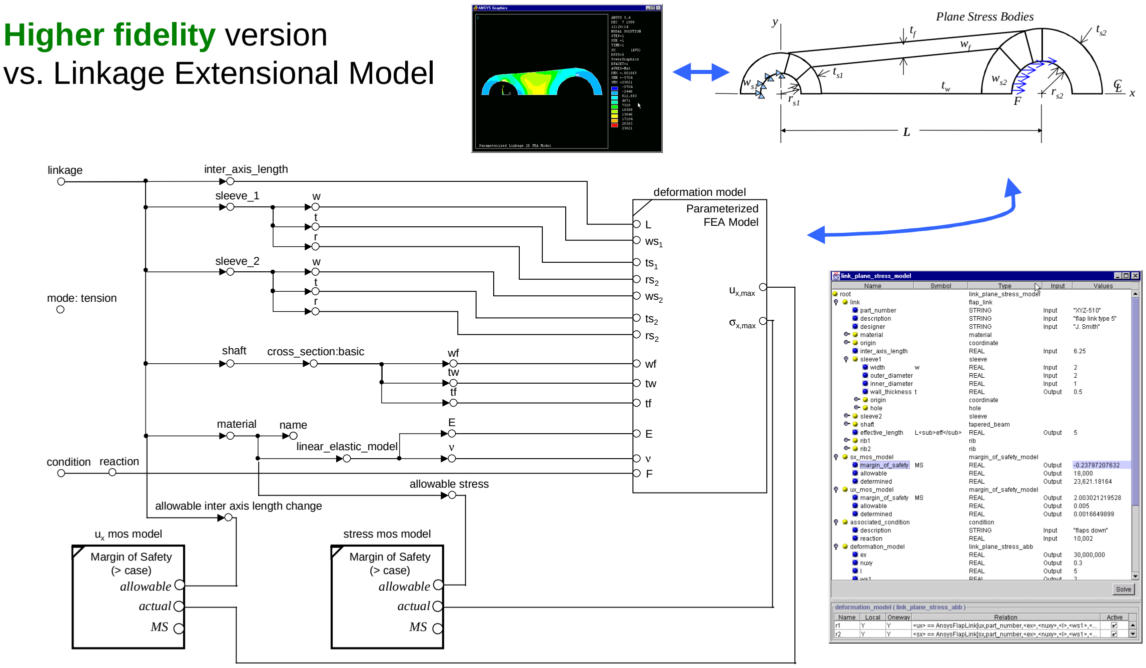


Figure 15 CBAM Usage of APM-based Idealizations



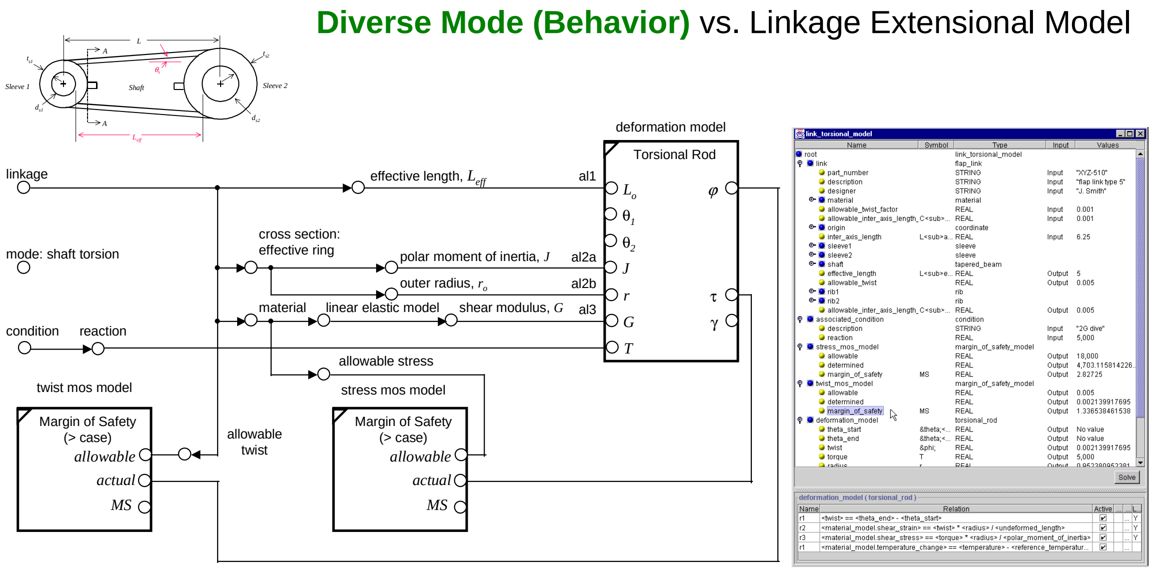
link_plane_stress_model

Name	Symbol	Type	Input	Values
root		link_plane_stress_model		
link		flap_link		
part_number		STRING	Input	"XYZ-510"
description		STRING	Input	"flap link type 5"
designer		STRING	Input	"J. Smith"
material		material		
origin		coordinate		
inter_axis_length		REAL	Input	6.25
sleeve1		sleeve		
width	w	REAL	Input	2
outer_diameter		REAL	Input	2
inner_diameter		REAL	Input	1
wall_thickness	t	REAL	Output	0.5
origin		coordinate		
hole		hole		
sleeve2		sleeve		
shaft		tapered_beam		
effective_length	L_{eff}	REAL	Output	5
rib1		rib		
rib2		rib		
sx_mos_model		margin_of_safety_model		
margin_of_safety	MS	REAL	Output	-0.23797207632
allowable		REAL	Output	18,000
determined		REAL	Output	23,621.18164
ux_mos_model		margin_of_safety_model		
margin_of_safety	MS	REAL	Output	2.003021219528
allowable		REAL	Output	0.005
determined		REAL	Output	0.0016649899
associated_condition		condition		
description		STRING	Input	"flaps down"
reaction		REAL	Input	10,002
deformation_model		link_plane_stress_abb		
ex		REAL	Output	30,000,000
nuxy		REAL	Output	0.3
l		REAL	Output	5

deformation_model (link_plane_stress_abb)

Name	Local	Oneway	Relation	Active
r1	Y	Y	<ux> == AnsysFlapLink[ux,part_number,<ex>,<nuxy>,<l>,<ws1>,<...	☑
r2	Y	Y	<sx> == AnsysFlapLink[sx,part_number,<ex>,<nuxy>,<l>,<ws1>,<...	☑

Figure 16 Higher Fidelity Flap Link CBAM: Linkage Plane Stress Model



Name	Symbol	Type	Input	Values
root		link_torsional_model		
link		flap_link		
part_number		STRING	Input	"XYZ-510"
description		STRING	Input	"flap link type 5"
designer		STRING	Input	"J. Smith"
material		material		
allowable_twist_factor		REAL	Input	0.001
allowable_inter_axis_length_	C<sub>...	REAL	Input	0.001
origin		coordinate		
inter_axis_length	L<sub>a...	REAL	Input	6.25
sleeve1		sleeve		
sleeve2		sleeve		
shaft		tapered_beam		
effective_length	L<sub>e...	REAL	Output	5
allowable_twist		REAL	Output	0.005
rib1		rib		
rib2		rib		
allowable_inter_axis_length_	C<sub>...	REAL	Output	0.005
associated_condition		condition		
description		STRING	Input	"2G dive"
reaction		REAL	Input	5,000
stress_mos_model		margin_of_safety_model		
allowable		REAL	Output	18,000
determined		REAL	Output	4,703.115814226..
margin_of_safety	MS	REAL	Output	2.82725
twist_mos_model		margin_of_safety_model		
allowable		REAL	Output	0.005
determined		REAL	Output	0.002139917695
margin_of_safety	MS	REAL	Output	1.336538461538
deformation_model		torsional_rod		
theta_start	θ<...	REAL	Output	No value
theta_end	θ<...	REAL	Output	No value
twist	φ	REAL	Output	0.002139917695
torque	T	REAL	Output	5,000
radius	r	REAL	Output	0.952380952381

Name	Relation	Active	...	...	L...
r1	<twist> == <theta_end> - <theta_start>	☑		...	Y
r2	<material_model.shear_strain> == <twist> * <radius> / <undeformed_length>	☑		...	Y
r3	<material_model.shear_stress> == <torque> * <radius> / <polar_moment_of_inertia>	☑		...	Y
r1	<material_model.temperature_change> == <temperature> - <reference_temperatur...	☑		...	

Figure 17 Alternate Mode Flap Link CBAM: Linkage Torsional Model

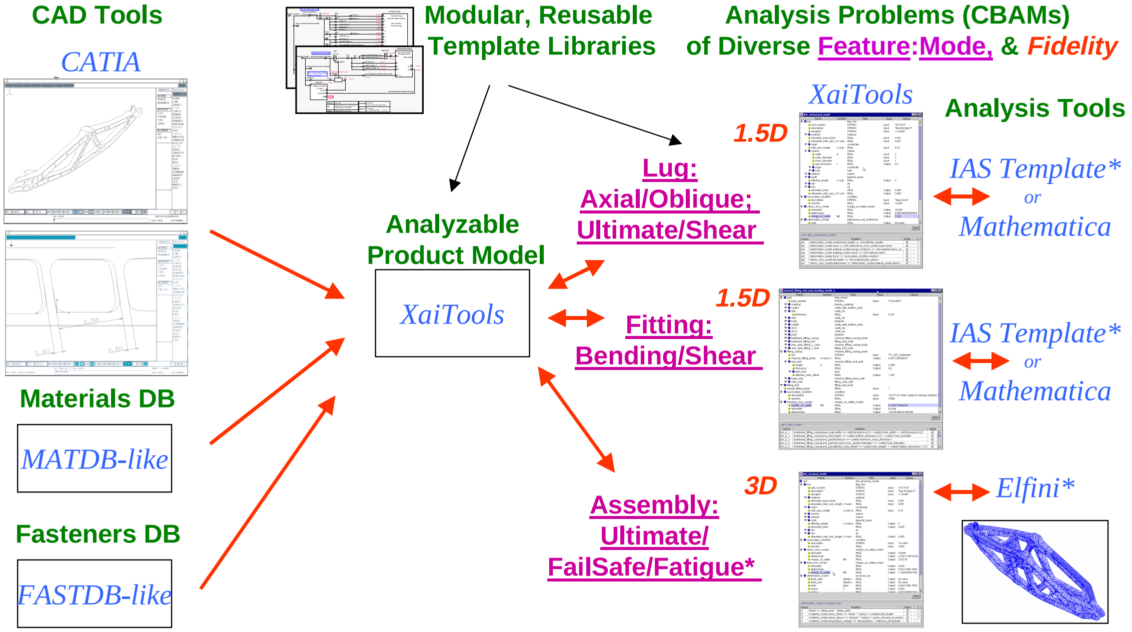


Figure 18 Flexible Design-Analysis Integration Using COBs:
Aerospace Case Study: “bike frame” [5]

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[5] Asterisks (*) indicate items not available as working prototype examples (all others are working examples)

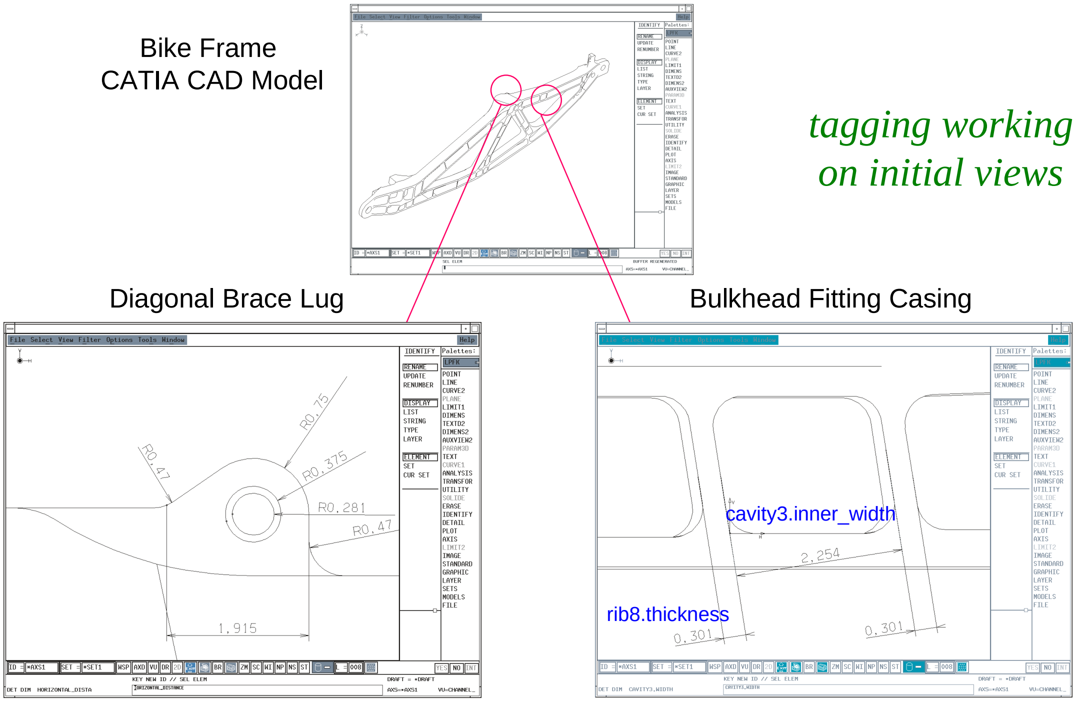
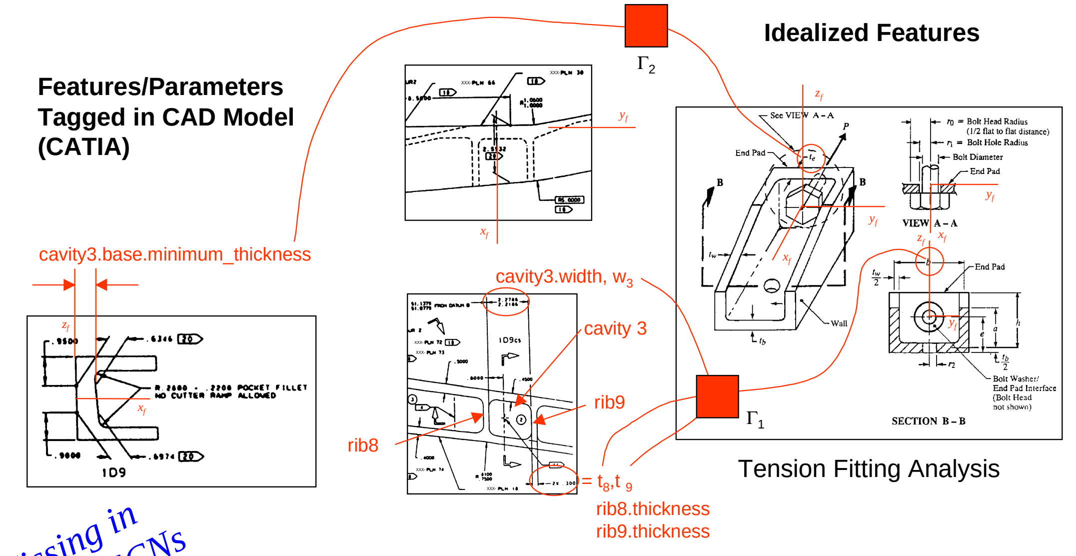


Figure 19 CATIA Tagged Parameters Used in Bike Frame APM



Γ_i - Relations between CAD parameters and idealized parameters

Γ_1 : b = cavity3.inner_width + rib8.thickness/2 + rib9.thickness/2

Γ_2 : t_e = cavity3.base.minimum_thickness

Figure 20 Explicit Representation of Analysis Fitting Idealizations

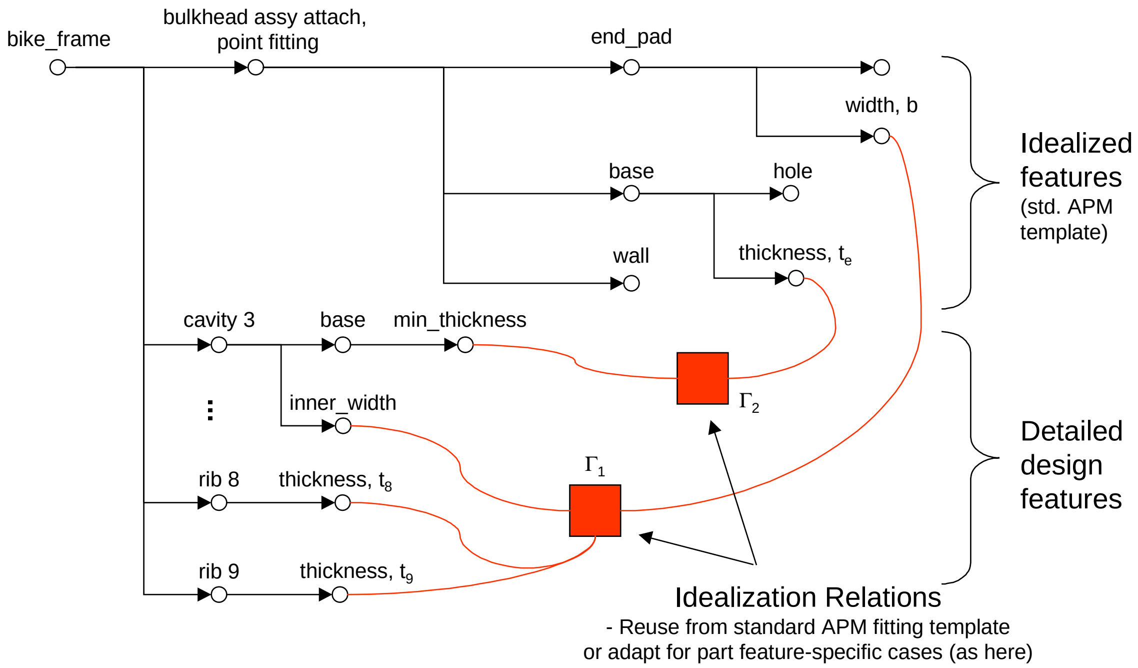
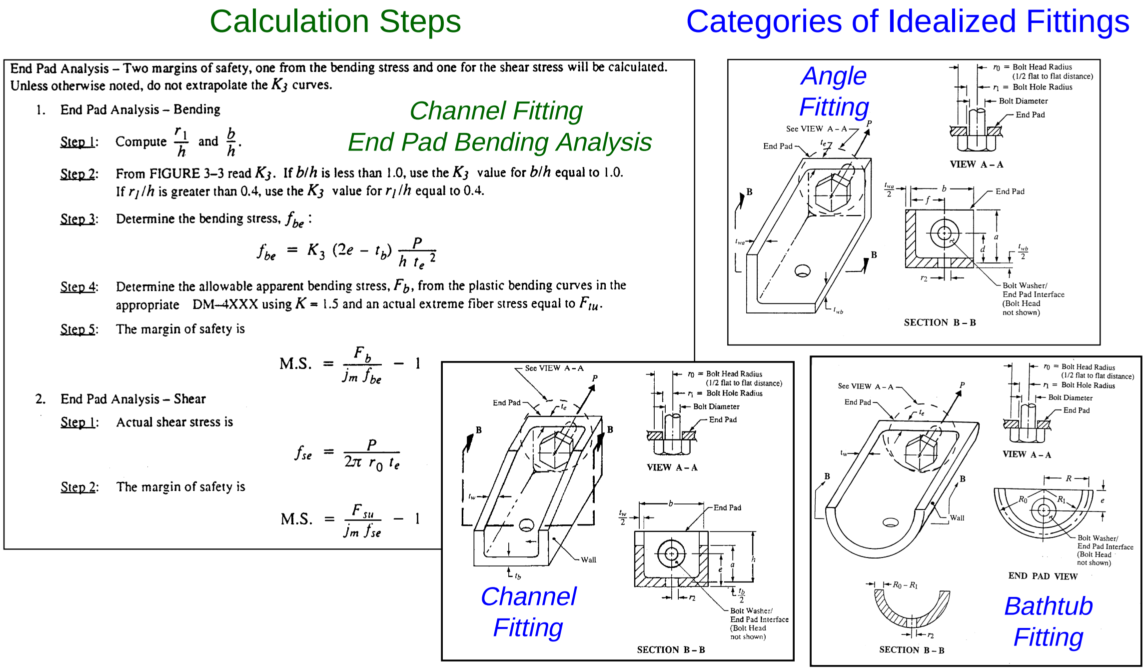


Figure 21 Capture of Analysis Fitting Idealizations in the Bike Frame APM



End Pad Analysis – Two margins of safety, one from the bending stress and one for the shear stress will be calculated. Unless otherwise noted, do not extrapolate the K_3 curves.

1. End Pad Analysis – Bending

Step 1: Compute $\frac{r_1}{h}$ and $\frac{b}{h}$.

Step 2: From FIGURE 3–3 read K_3. If b/h is less than 1.0, use the K_3 value for b/h equal to 1.0. If r_1/h is greater than 0.4, use the K_3 value for r_1/h equal to 0.4.

Step 3: Determine the bending stress, f_{be}:

$$f_{be} = K_3 \, (2e - t_b) \frac{P}{h \, t_e{}^2}$$

Step 4: Determine the allowable apparent bending stress, F_b, from the plastic bending curves in the appropriate DM–4XXX using $K = 1.5$ and an actual extreme fiber stress equal to F_{tu}.

Step 5: The margin of safety is

$$\text{M.S.} = \frac{F_b}{j_m \, f_{be}} - 1$$

2. End Pad Analysis – Shear

Step 1: Actual shear stress is

$$f_{se} = \frac{P}{2\pi \, r_0 \, t_e}$$

Step 2: The margin of safety is

$$\text{M.S.} = \frac{F_{su}}{j_m \, f_{se}} - 1$$

Figure 22 Today’s Fitting Design Guide Documentation

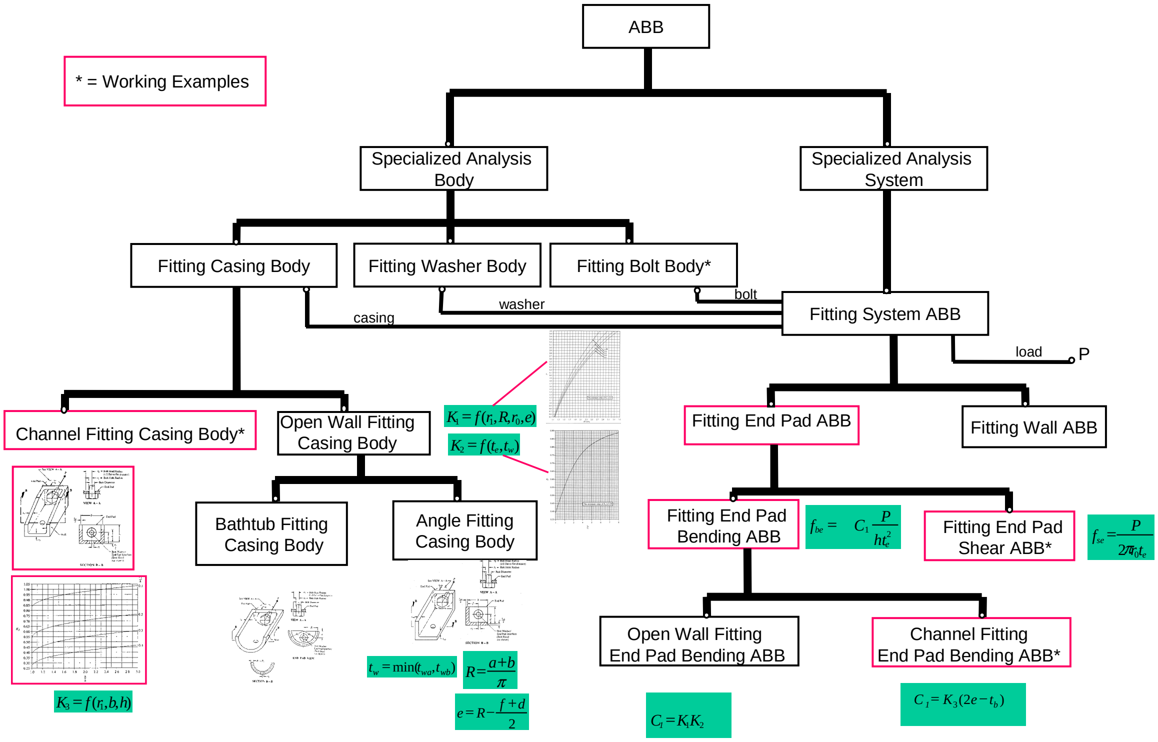
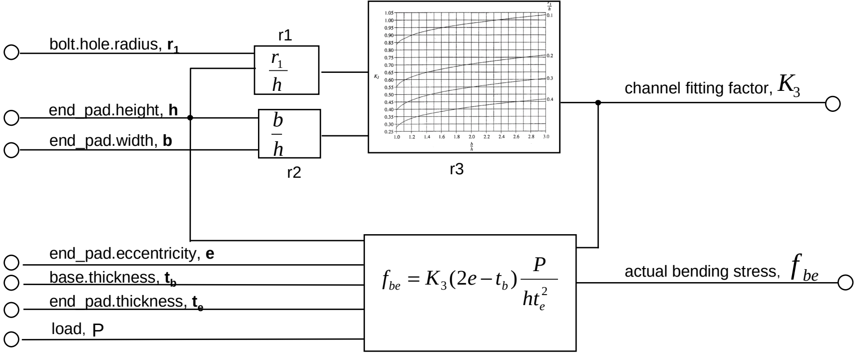


Figure 23 Decomposition of Design Guide as Object-Oriented Fitting ABBs

End Pad Bending Analysis



End Pad Shear Analysis

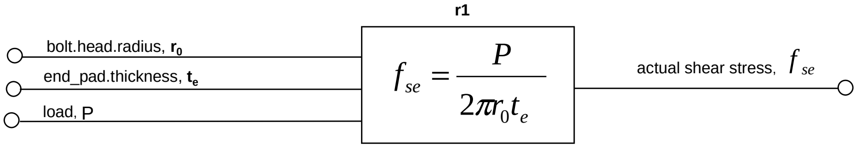
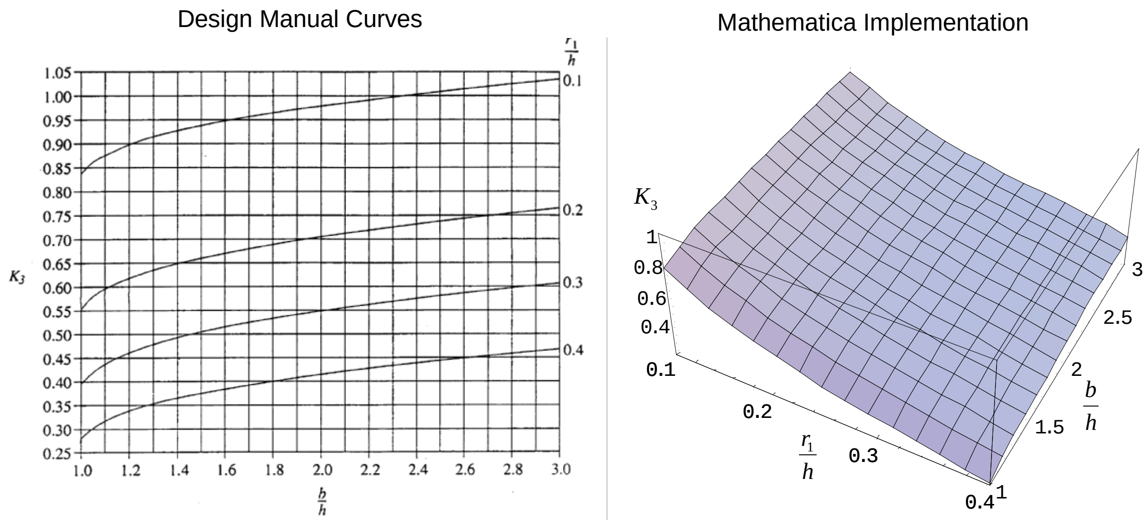
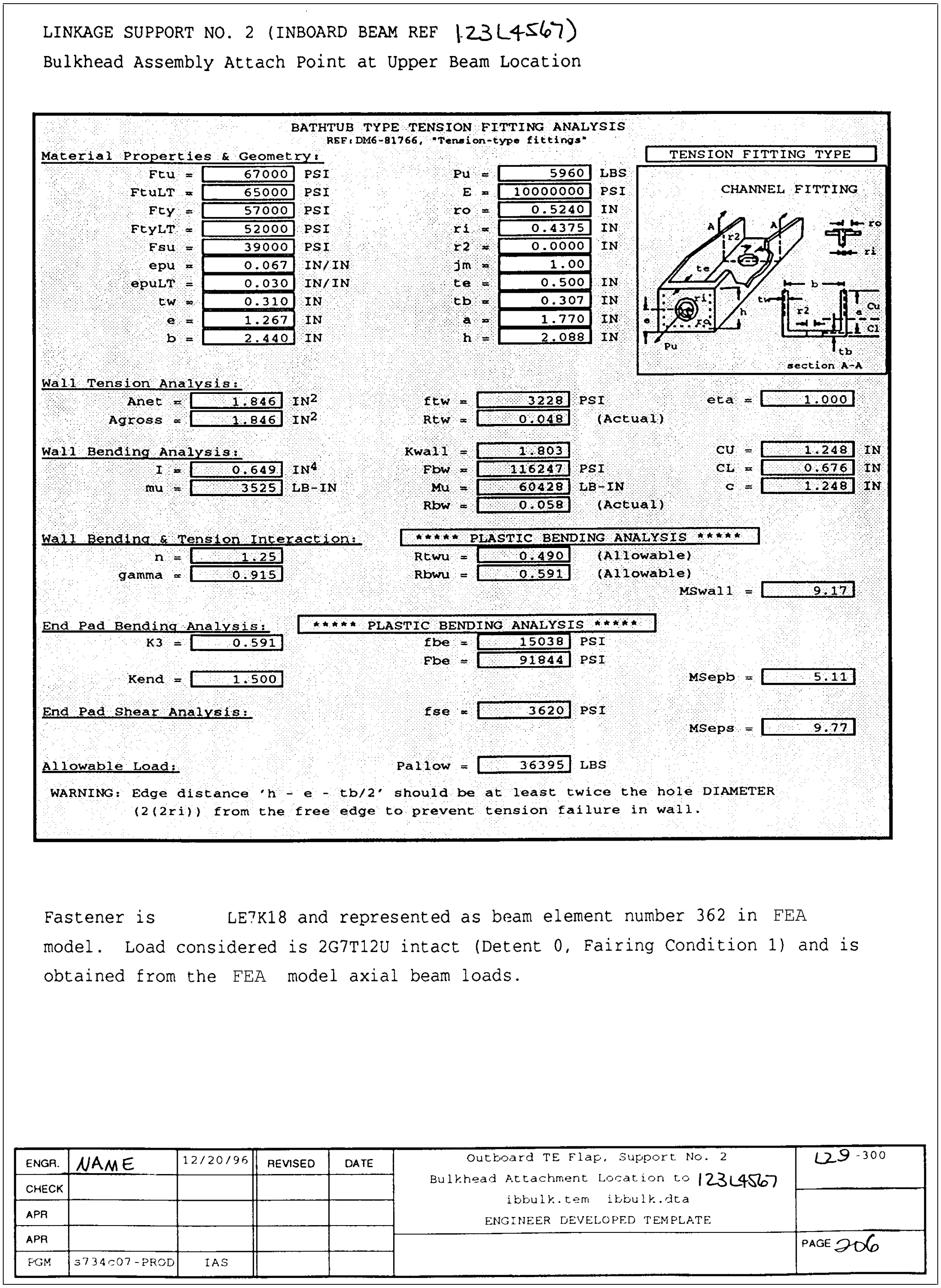


Figure 24 Channel Fitting System ABBs for End Pad Analysis


Design Manual Curves

Mathematica Implementation

Figure 25 Implementation of Channel Fitting Factor Curves
as a Reusable Relation in a General Purpose Math Tool



LINKAGE SUPPORT NO. 2 (INBOARD BEAM REF 1234567)

Bulkhead Assembly Attach Point at Upper Beam Location

BATHTUB TYPE TENSION FITTING ANALYSIS

REF: DM6-81766, "Tension-type fittings"

Material Properties & Geometry:

Ftu = 67000 PSI
FtuLT = 65000 PSI
Fty = 57000 PSI
FtyLT = 52000 PSI
Fsu = 39000 PSI
epu = 0.067 IN/IN
epuLT = 0.030 IN/IN
tw = 0.310 IN
e = 1.267 IN
b = 2.440 IN

Pu = 5960 LBS
E = 10000000 PSI
ro = 0.5240 IN
ri = 0.4375 IN
r2 = 0.0000 IN
jm = 1.00
te = 0.500 IN
tb = 0.307 IN
a = 1.770 IN
h = 2.088 IN

TENSION FITTING TYPE

CHANNEL FITTING

Wall Tension Analysis:

Anet = 1.846 IN^2
Agross = 1.846 IN^2

ftw = 3228 PSI
Rtw = 0.048 (Actual)

eta = 1.000

Wall Bending Analysis:

I = 0.649 IN^4
mu = 3525 LB-IN

Kwall = 1.803
Fbw = 116247 PSI
Mu = 60428 LB-IN
Rbw = 0.058 (Actual)

CU = 1.248 IN
CL = 0.676 IN
c = 1.248 IN

Wall Bending & Tension Interaction:

n = 1.25
gamma = 0.915

***** PLASTIC BENDING ANALYSIS *****

Rtwu = 0.490 (Allowable)
Rbwu = 0.591 (Allowable)

MSwall = 9.17

End Pad Bending Analysis:

K3 = 0.591
Kend = 1.500

***** PLASTIC BENDING ANALYSIS *****

fbe = 15038 PSI
Fbe = 91844 PSI

MSepb = 5.11

End Pad Shear Analysis:

fse = 3620 PSI

MSeps = 9.77

Allowable Load:

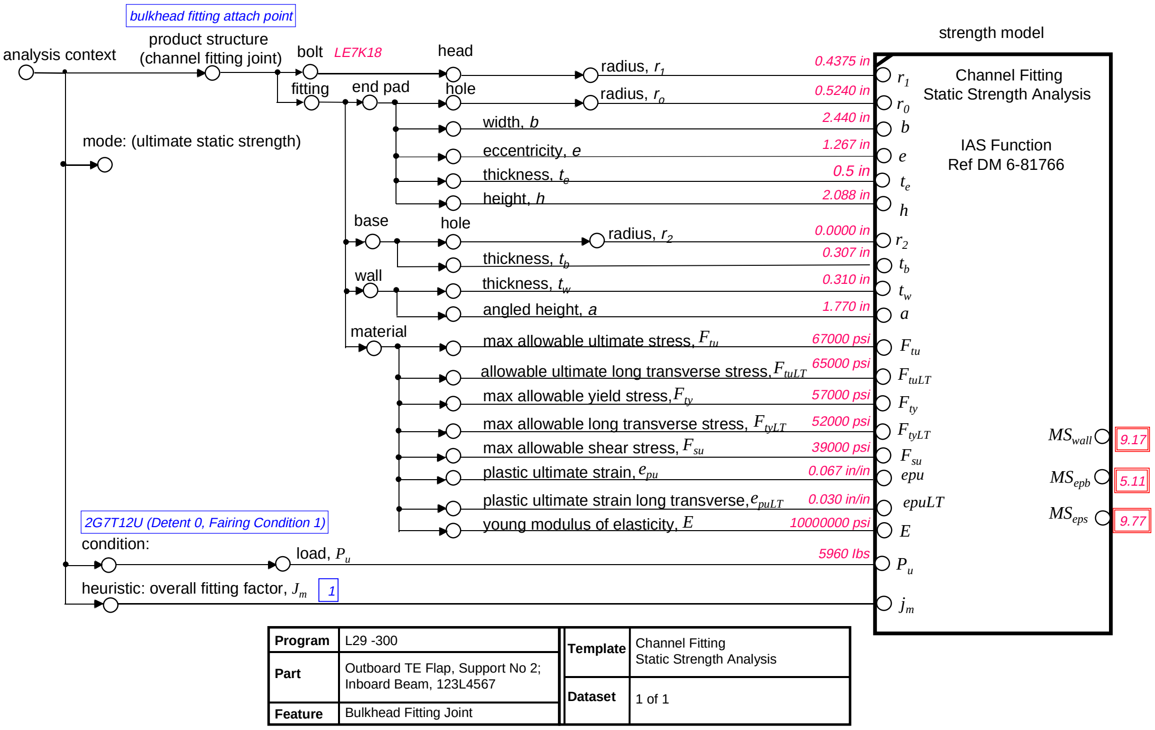
Pallow = 36395 LBS

WARNING: Edge distance 'h - e - tb/2' should be at least twice the hole DIAMETER (2(2ri)) from the free edge to prevent tension failure in wall.

Fastener is LE7K18 and represented as beam element number 362 in FEA model. Load considered is 2G7T12U intact (Detent 0, Fairing Condition 1) and is obtained from the FEA model axial beam loads.

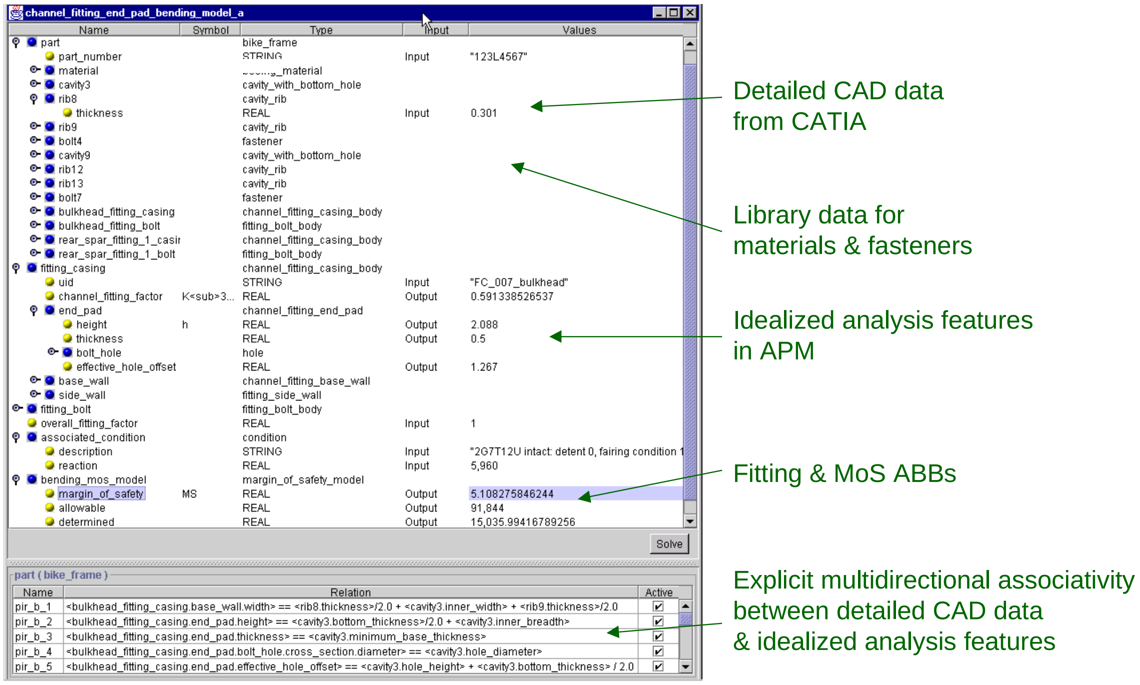
ENGR.	NAME	12/20/96	REVISED	DATE	Outboard TE Flap, Support No. 2 Bulkhead Attachment Location to 1234567 ibbulk.tem ibbulk.dta ENGINEER DEVELOPED TEMPLATE	L29 -300
CHECK						
APR						
APR						PAGE 206
PGM	s734c07-PROD	IAS				

Figure 26 Typical Strength Check Note (SCN):
Bike Frame Bulkhead Fitting Analyses



Program	L29 -300	**Template**	Channel Fitting Static Strength Analysis
Part	Outboard TE Flap, Support No 2; Inboard Beam, 123L4567	**Dataset**	1 of 1
Feature	Bulkhead Fitting Joint		

Figure 27 Bike Frame Bulkhead Fitting Analysis:
Implementation as a CBAM (Constraint Schematic Instance View)



Name	Symbol	Type	Input	Values
part		bike_frame		
part_number		STRING	Input	"123L4567"
material		......_material		
cavity3		cavity_with_bottom_hole		
rib8		cavity_rib		
thickness		REAL	Input	0.301
rib9		cavity_rib		
bolt4		fastener		
cavity9		cavity_with_bottom_hole		
rib12		cavity_rib		
rib13		cavity_rib		
bolt7		fastener		
bulkhead_fitting_casing		channel_fitting_casing_body		
bulkhead_fitting_bolt		fitting_bolt_body		
rear_spar_fitting_1_casir		channel_fitting_casing_body		
rear_spar_fitting_1_bolt		fitting_bolt_body		
fitting_casing		channel_fitting_casing_body		
uid		STRING	Input	"FC_007_bulkhead"
channel_fitting_factor	K<sub>3...	REAL	Output	0.591338526537
end_pad		channel_fitting_end_pad		
height	h	REAL	Output	2.088
thickness		REAL	Output	0.5
bolt_hole		hole		
effective_hole_offset		REAL	Output	1.267
base_wall		channel_fitting_base_wall		
side_wall		fitting_side_wall		
fitting_bolt		fitting_bolt_body		
overall_fitting_factor		REAL	Input	1
associated_condition		condition		
description		STRING	Input	"2G7T12U intact: detent 0, fairing condition 1
reaction		REAL	Input	5,960
bending_mos_model		margin_of_safety_model		
margin_of_safety	MS	REAL	Output	5.108275846244
allowable		REAL	Output	91,844
determined		REAL	Output	15,035.99416789256

part (bike_frame)

Name	Relation	Active
pir_b_1	<bulkhead_fitting_casing.base_wall.width> == <rib8.thickness>/2.0 + <cavity3.inner_width> + <rib9.thickness>/2.0	☑
pir_b_2	<bulkhead_fitting_casing.end_pad.height> == <cavity3.bottom_thickness>/2.0 + <cavity3.inner_breadth>	☑
pir_b_3	<bulkhead_fitting_casing.end_pad.thickness> == <cavity3.minimum_base_thickness>	☑
pir_b_4	<bulkhead_fitting_casing.end_pad.bolt_hole.cross_section.diameter> == <cavity3.hole_diameter>	☑
pir_b_5	<bulkhead_fitting_casing.end_pad.effective_hole_offset> == <cavity3.hole_height> + <cavity3.bottom_thickness> / 2.0	☑

Detailed CAD data
from CATIA

Library data for
materials & fasteners

Idealized analysis features
in APM

Fitting & MoS ABBs

Explicit multidirectional associativity
between detailed CAD data
& idealized analysis features

Figure 28 Bike Frame Bulkhead Fitting Analysis:
Results from CBAM *XaiTools* Implementation (as decomposed COB libraries)

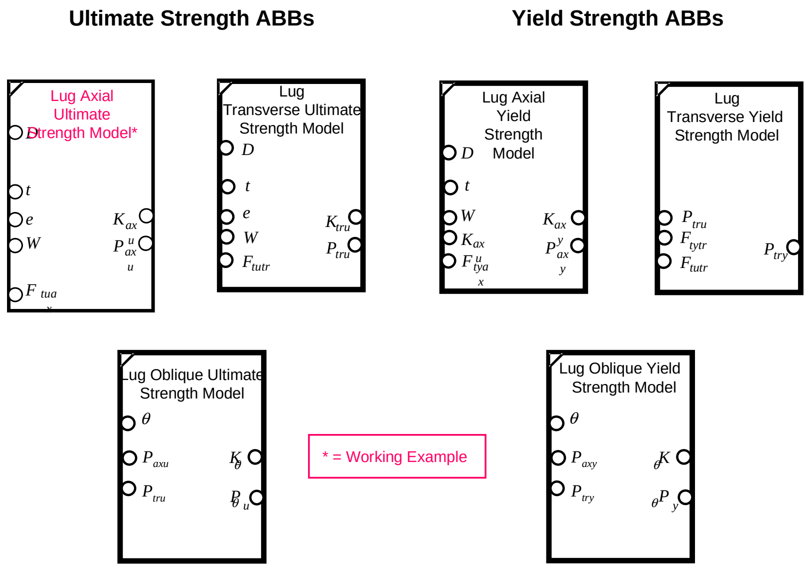


Figure 29 Decomposition of Lug Design Guide into ABBs

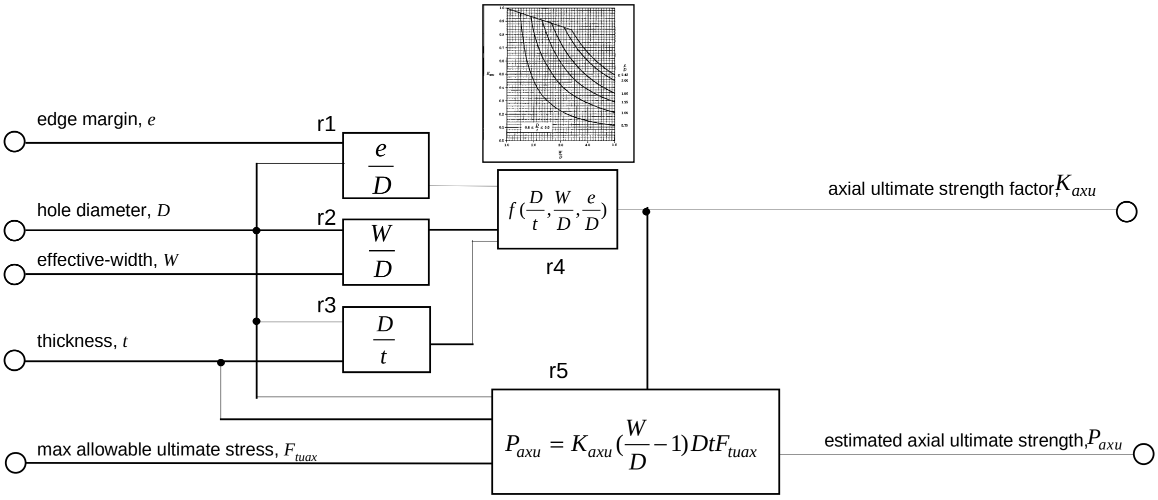


Figure 30 Internal Workings of the Lug Axial Ultimate Strength Model ABB
(Constraint Schematic View)

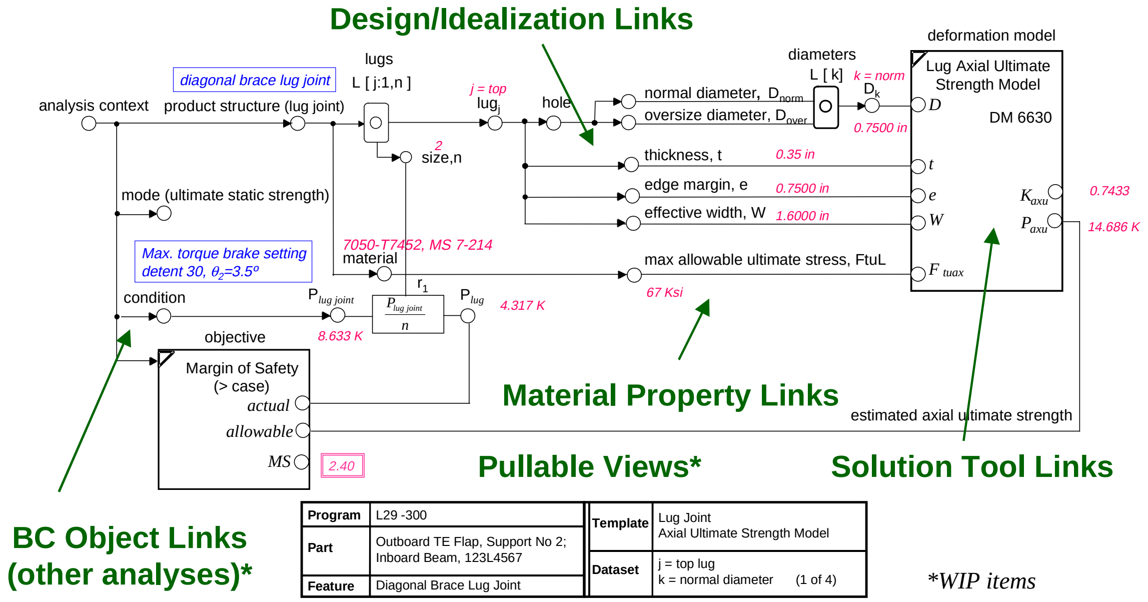


Figure 31 Bike Frame Usage of a Lug CBAM

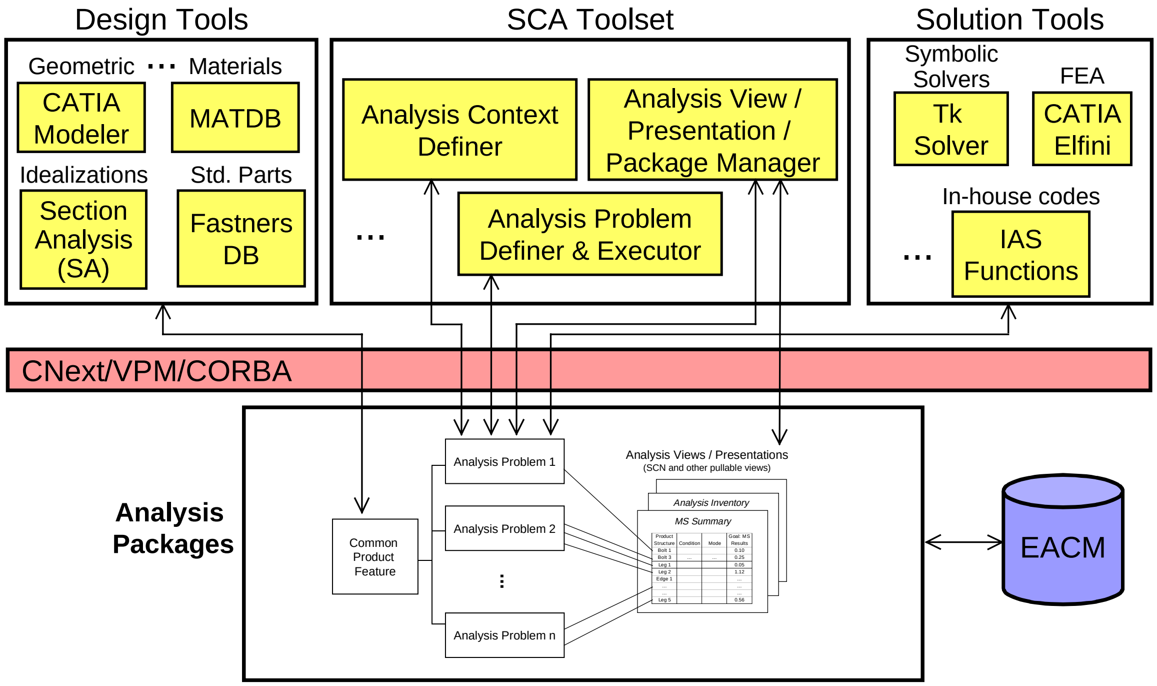


Figure 32 Elements of a Next Generation Stress Analysis Architecture

Attachment A – XaiTools™ Users Guide