An Introduction to X-Analysis Integration (XAI)

Russell S. Peak

Georgia Tech

Engineering Information Systems Lab

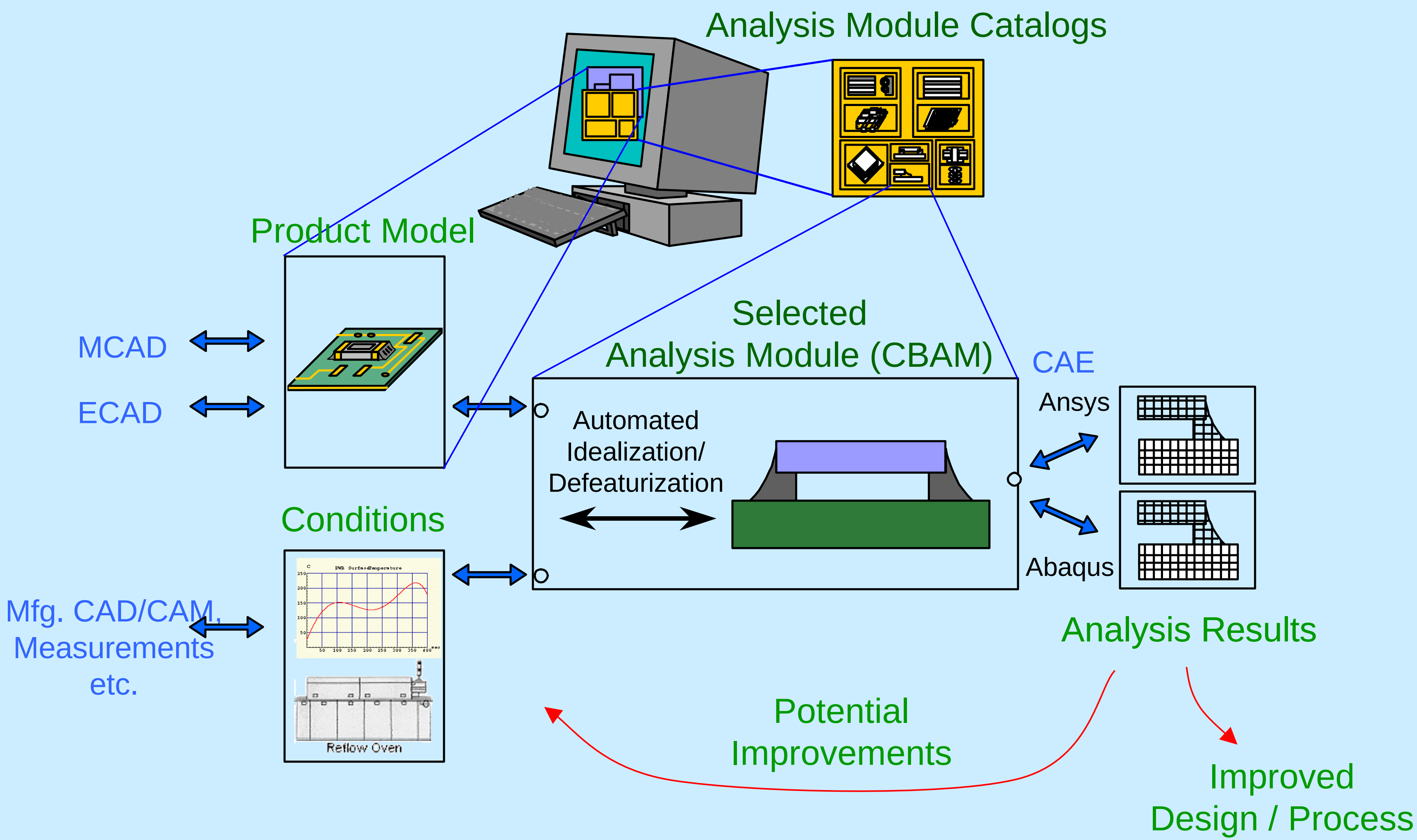
eislab.gatech.edu

Handout 6

Outline

- Analysis Integration Challenges
- Introduction to Constrained Objects (COBs)
- Overview of COB-based XAI
- Example Applications
  - Electronic Packaging Thermomechanical Analysis
  - Aerospace Structural Analysis
- Summary

Analysis Integration Thrust



CBAM= context-based analysis model

X-Analysis Integration
(X=Design, Mfg., etc.)

- **Goal:**

Improve product engineering processes by integrating analysis models with other life cycle models

- **Challenges:**
  - Heterogeneous Transformations
  - Diversity: CAD/CAM/CAX Models, Disciplines, Fidelity, Tools, etc.
- **One Approach:**

The Multi-Representation Architecture (MRA)

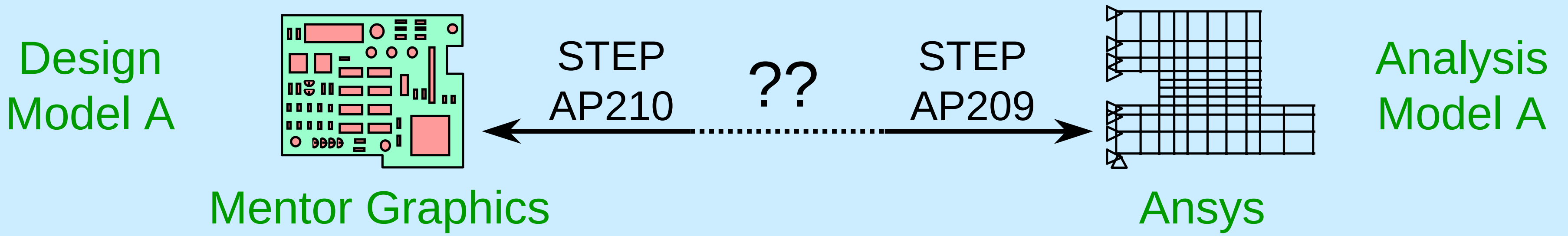
- **Initial Focus:**

Automation of routine analysis for design

Analysis Integration Challenges: Heterogeneous Transformations

- Homogeneous Transformation

- Heterogeneous Transformation

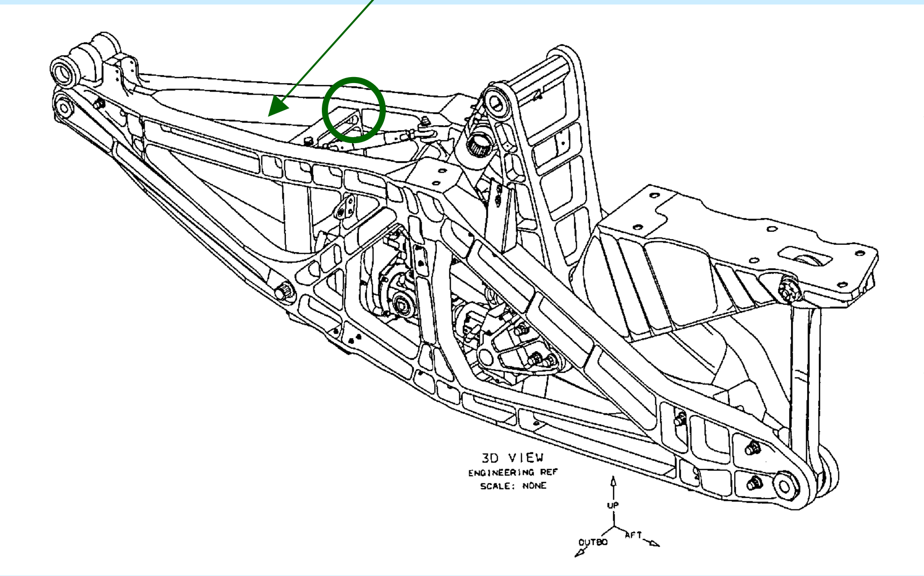


Multifidelity Analysis

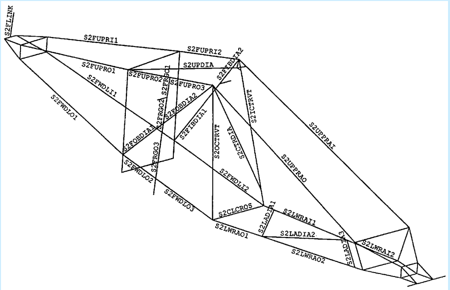
Design Model (MCAD)

Analysis Models (MCAE)

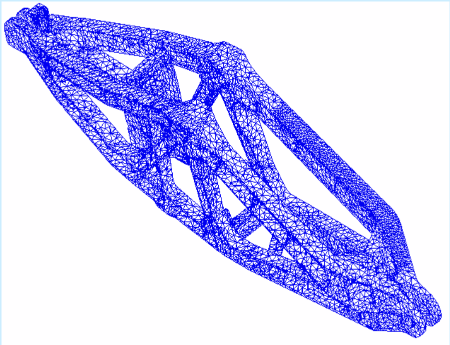
flap support assembly inboard beam



1D Beam/Stick Model

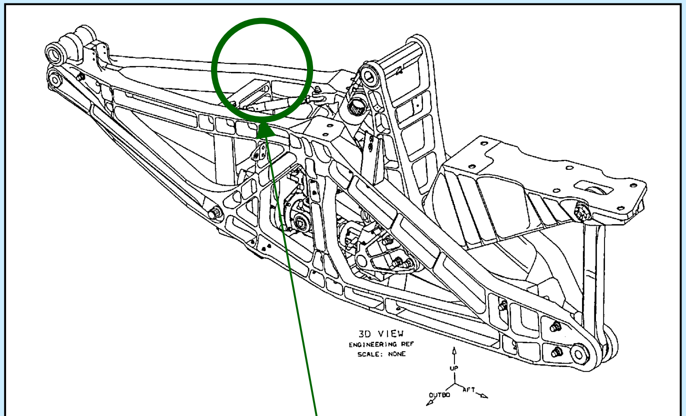


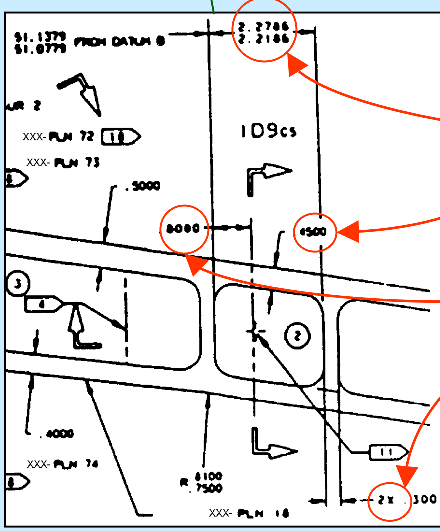
3D Continuum/Brick Model



Design Geometry - Analysis Geometry Mismatch

Detailed Design Model





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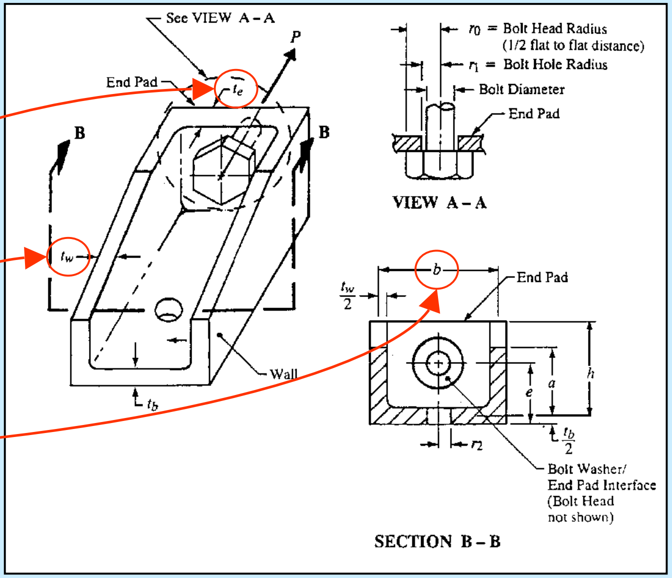
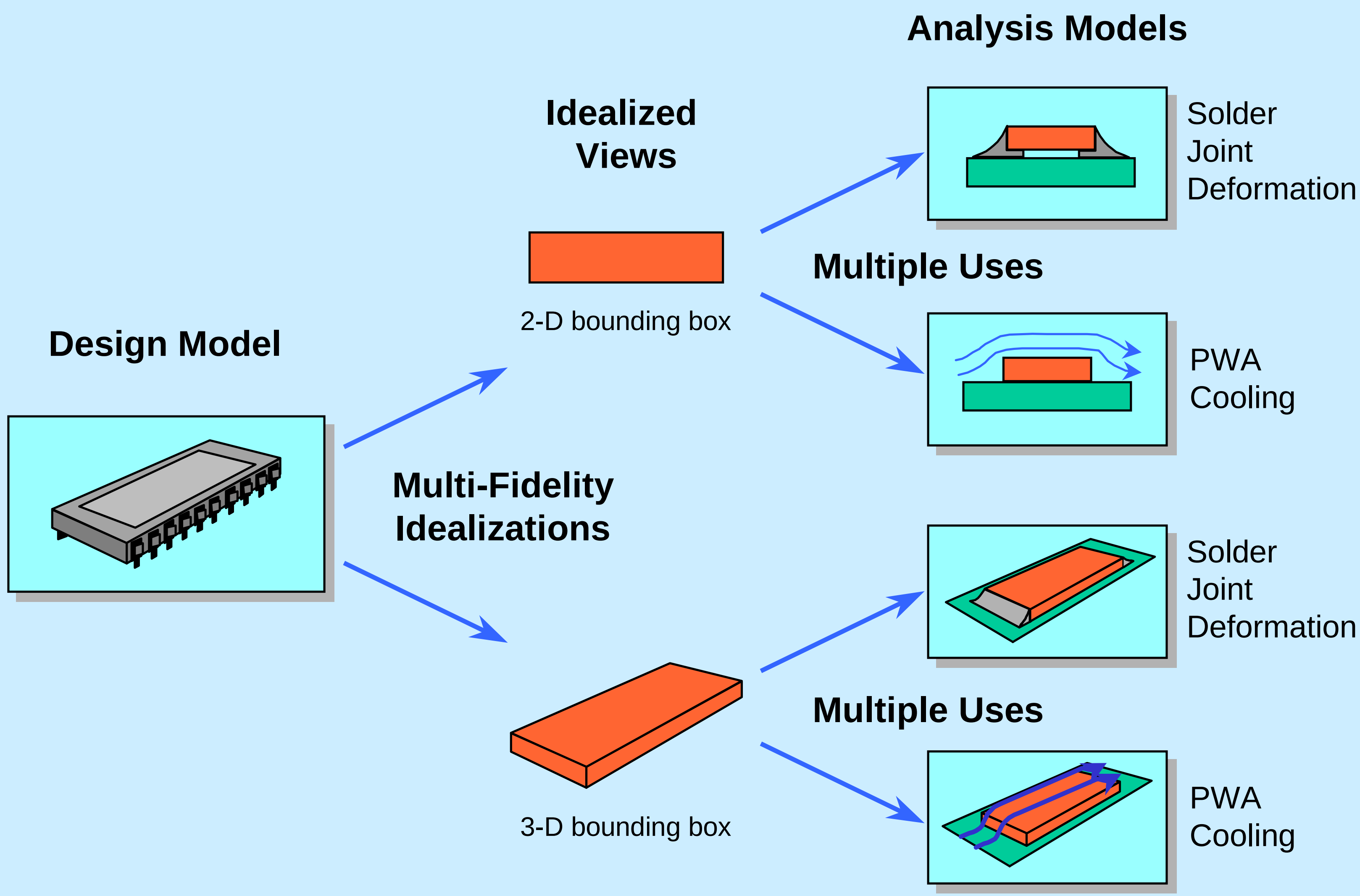
Idealizations

Analysis Model (with Idealized Features)



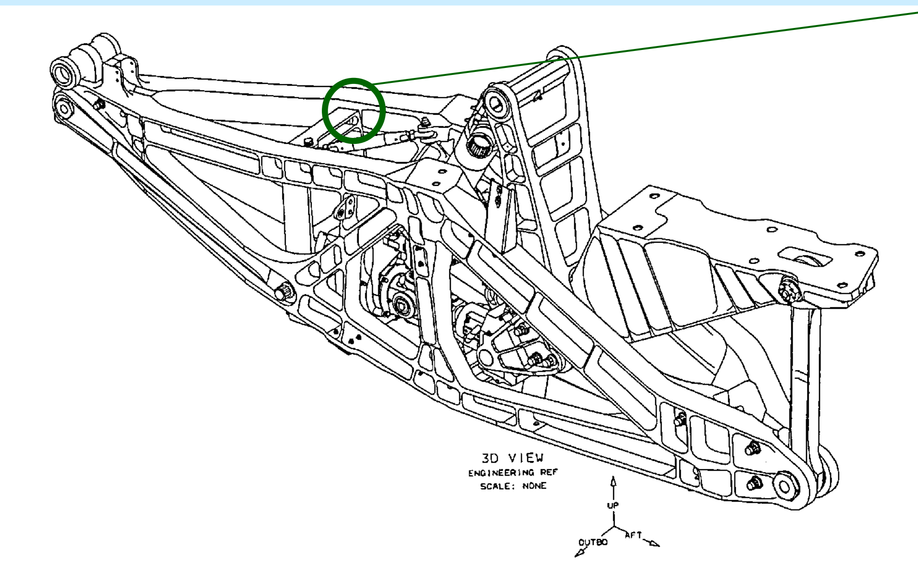
Tension Fitting Analysis

Multi-Fidelity, Multi-Usage Idealizations



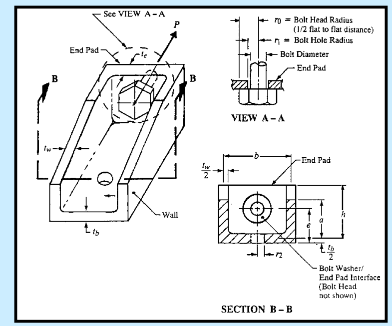
Multilevel Analysis

Design Model (MCAD)

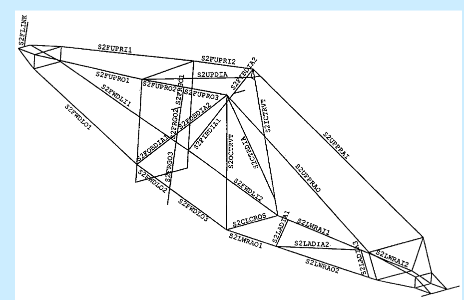


Analysis Models (MCAE)

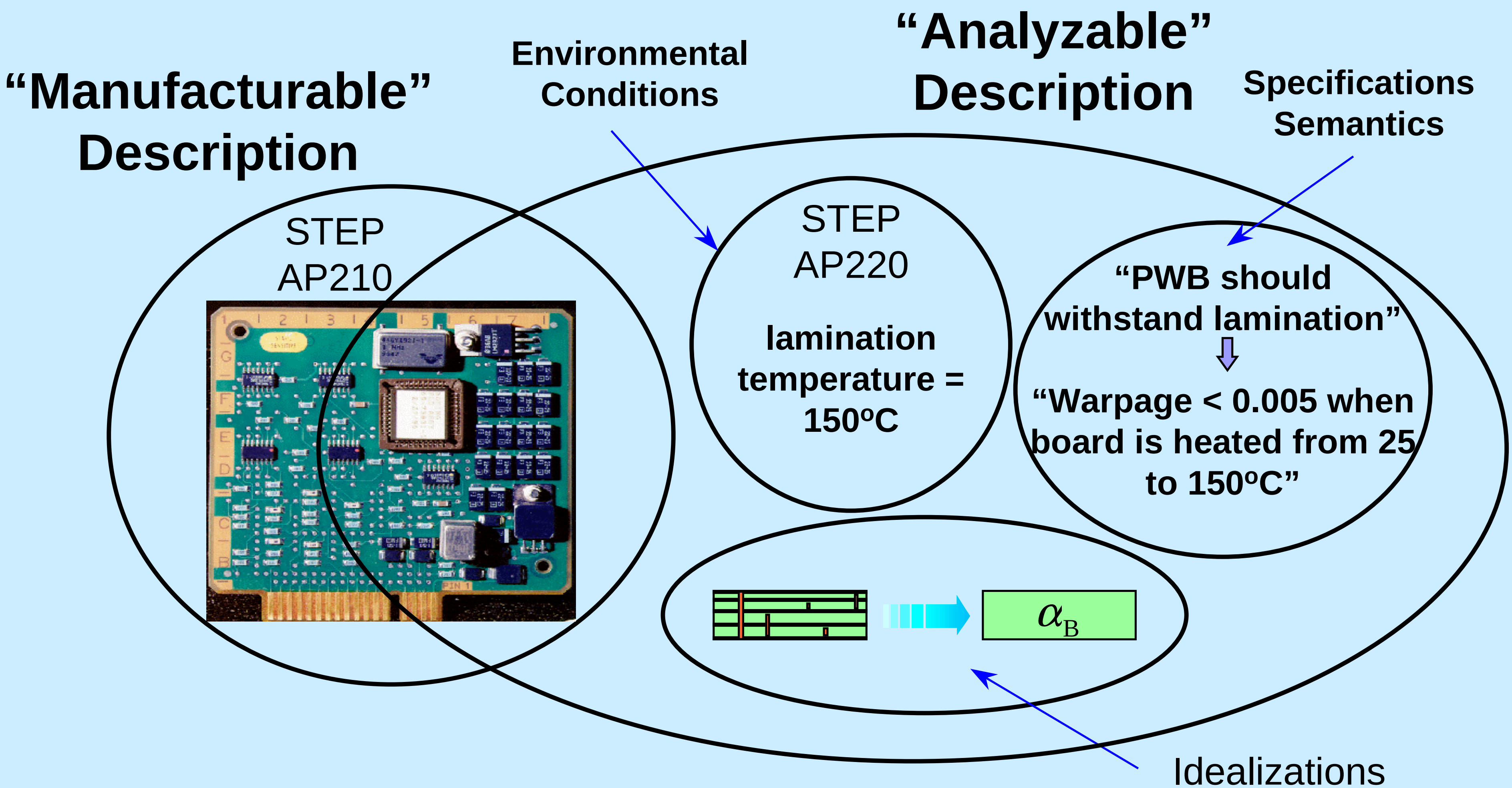
Part Feature Level Model



Assembly Level Model



Analysis Integration Challenges: Information Diversity



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- Introduction to Constrained Objects (COBs)
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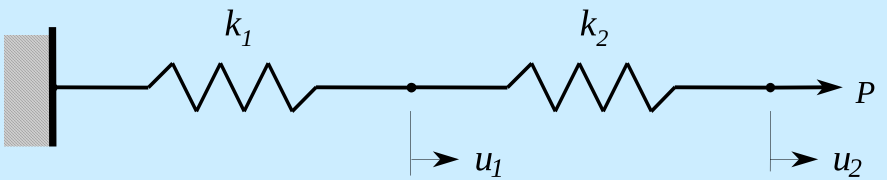
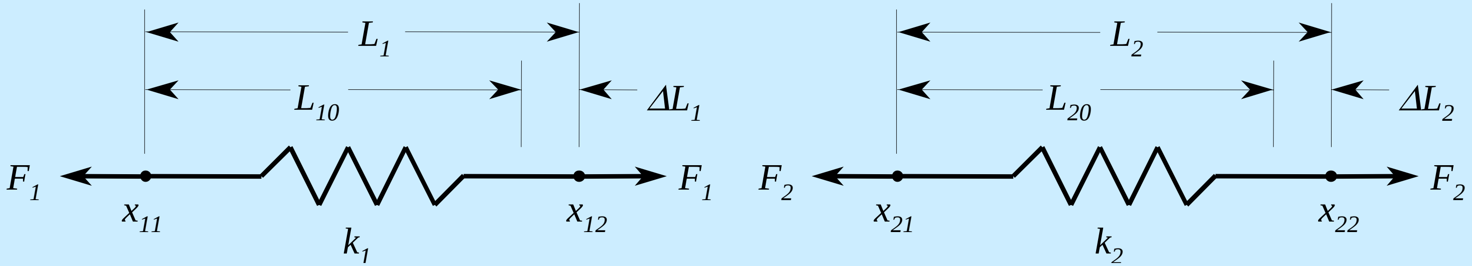
Traditional Mathematical Representation

Two Spring System

System Figure



Free Body Diagrams



Variables and Relations

Kinematic Relations →

Constitutive Relations →

$r_{11} : L_1 = x_{12} - x_{11}$

$r_{12} : \Delta L_1 = L_1 - L_{10}$

$r_{13} : F_1 = k_1 \Delta L_1$

$r_{21} : L_2 = x_{22} - x_{21}$

$r_{22} : \Delta L_2 = L_2 - L_{20}$

$r_{23} : F_2 = k_2 \Delta L_2$

Boundary Conditions ←

$bc_1 : x_{11} = 0$

$bc_2 : x_{12} = x_{21}$

$bc_3 : F_1 = F_2$

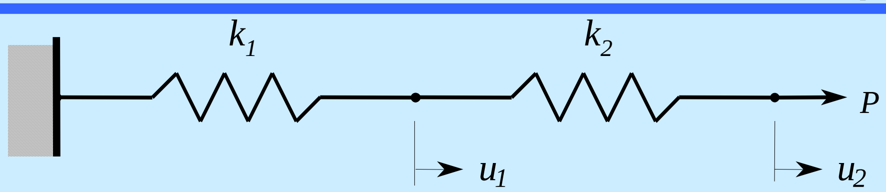
$bc_4 : F_2 = P$

$bc_5 : u_1 = \Delta L_1$

$bc_6 : u_2 = \Delta L_2 + u_1$

Constraint Graph

Two Spring System



$r_{11} : L_1 = x_{12} - x_{11}$

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$r_{22} : \Delta L_2 = L_2 - L_{20}$

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$bc_1 : x_{11} = 0$

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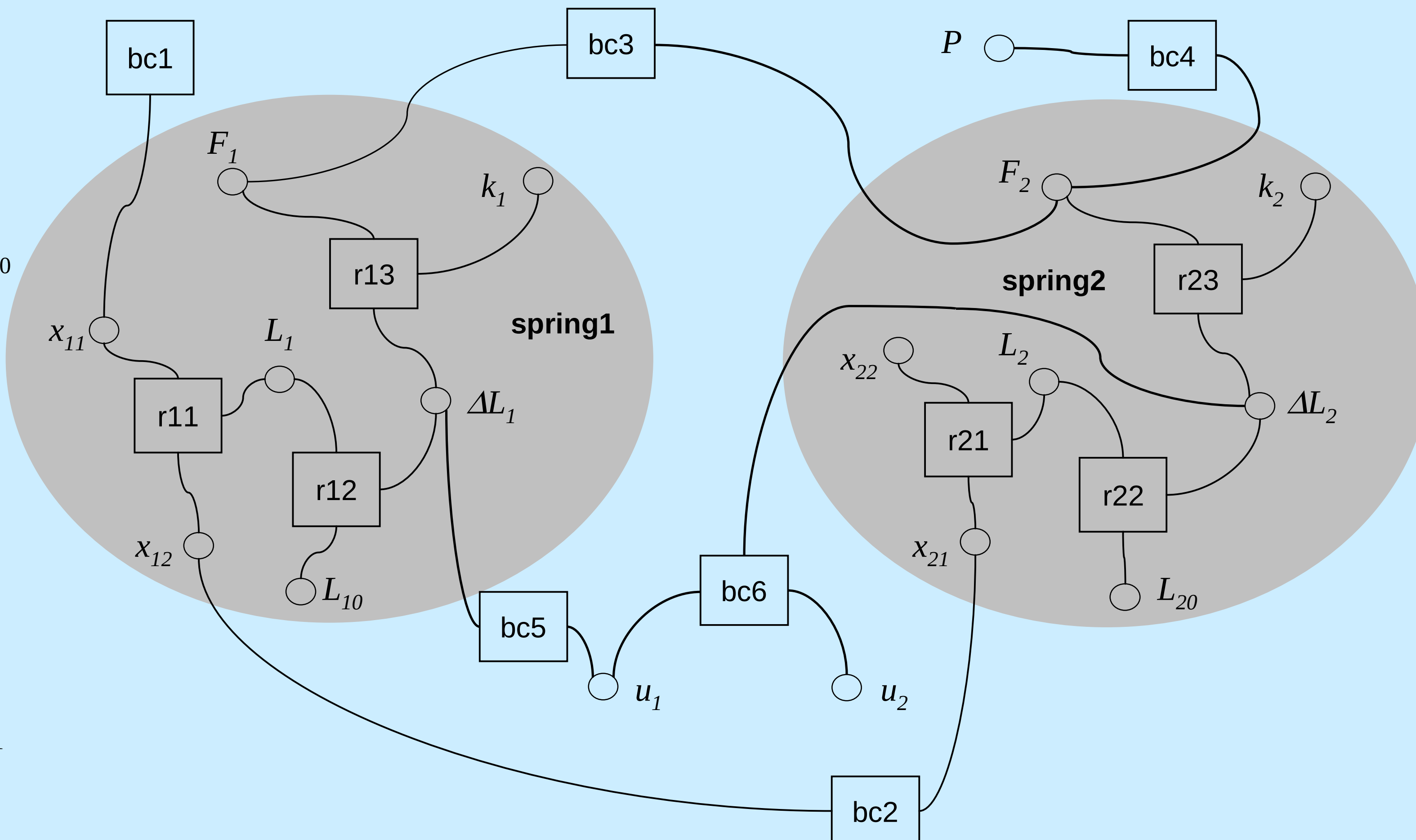
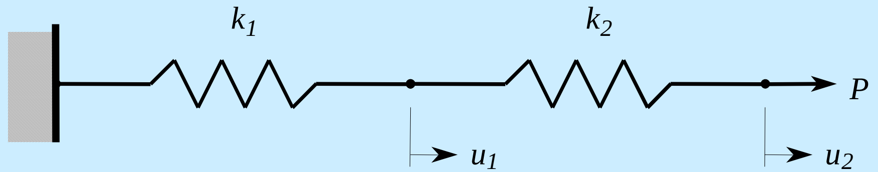


COB Constraint Schematic

Two Spring System



Analysis Primitives with Encapsulated Relations

$r_{11} : L_1 = x_{12} - x_{11}$

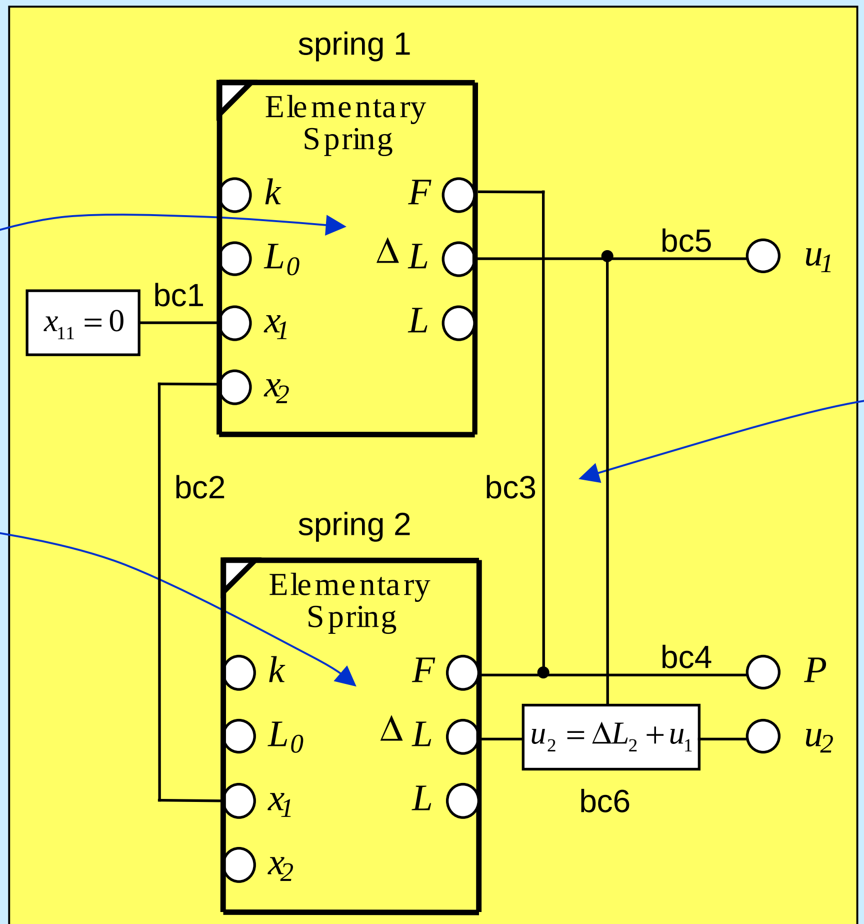
$r_{12} : \Delta L_1 = L_1 - L_{10}$

$r_{13} : F_1 = k_1 \Delta L_1$

$r_{21} : L_2 = x_{22} - x_{21}$

$r_{22} : \Delta L_2 = L_2 - L_{20}$

$r_{23} : F_2 = k_2 \Delta L_2$



System-Level Relations (Boundary Conditions)

$bc_1 : x_{11} = 0$

$bc_2 : x_{12} = x_{21}$

$bc_3 : F_1 = F_2$

$bc_4 : F_2 = P$

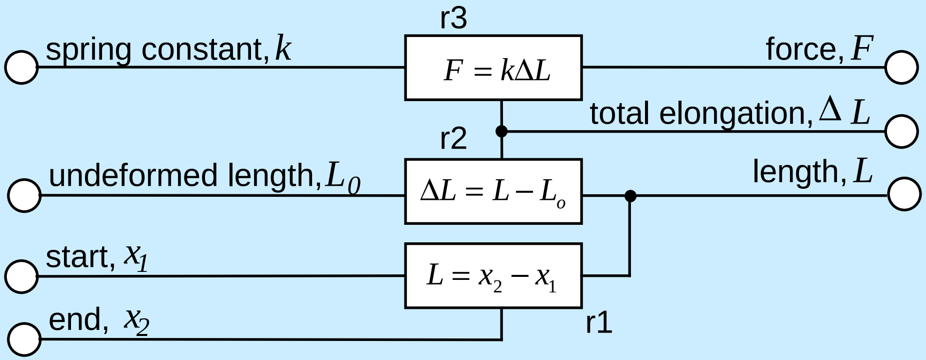
$bc_5 : u_1 = \Delta L_1$

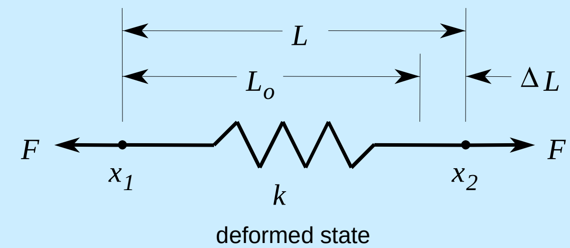
$bc_6 : u_2 = \Delta L_2 + u_1$

COB Structure: Graphical Forms

Spring Primitive

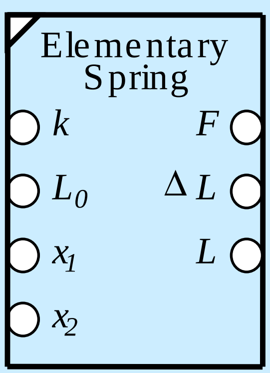
Constraint Schematic





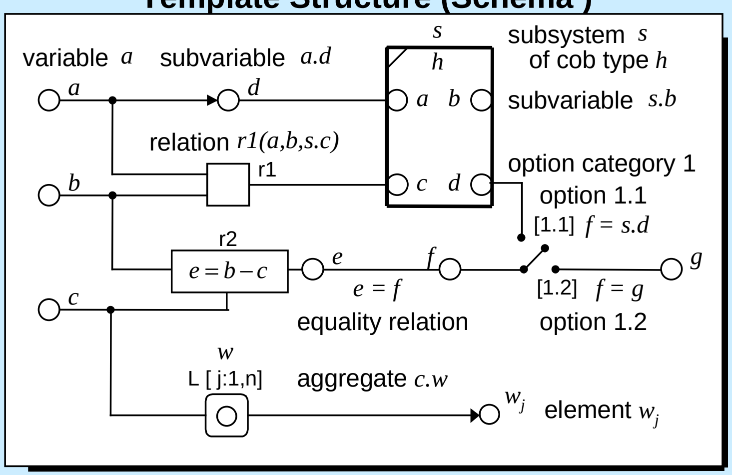
Subsystem View

(for reuse by other COBs)



Basic Constraint Schematic Notation

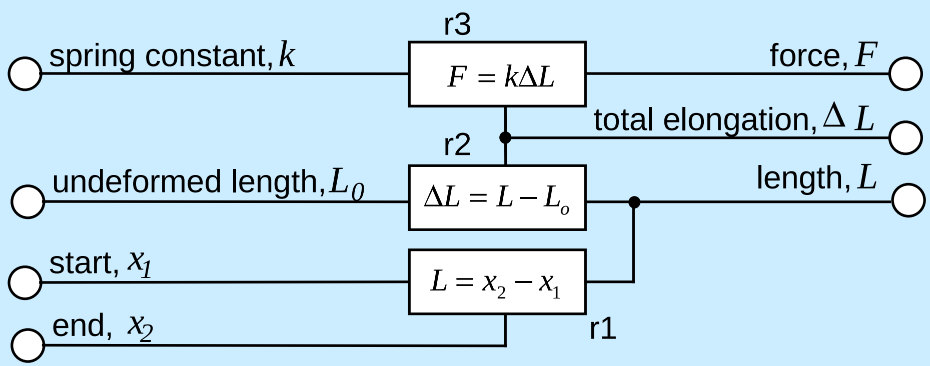
Template Structure (Schema)



COB Structure: Lexical Form

Spring Primitive

Constraint Schematic

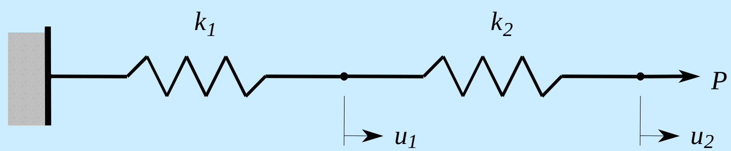


Lexical COB Schema Template

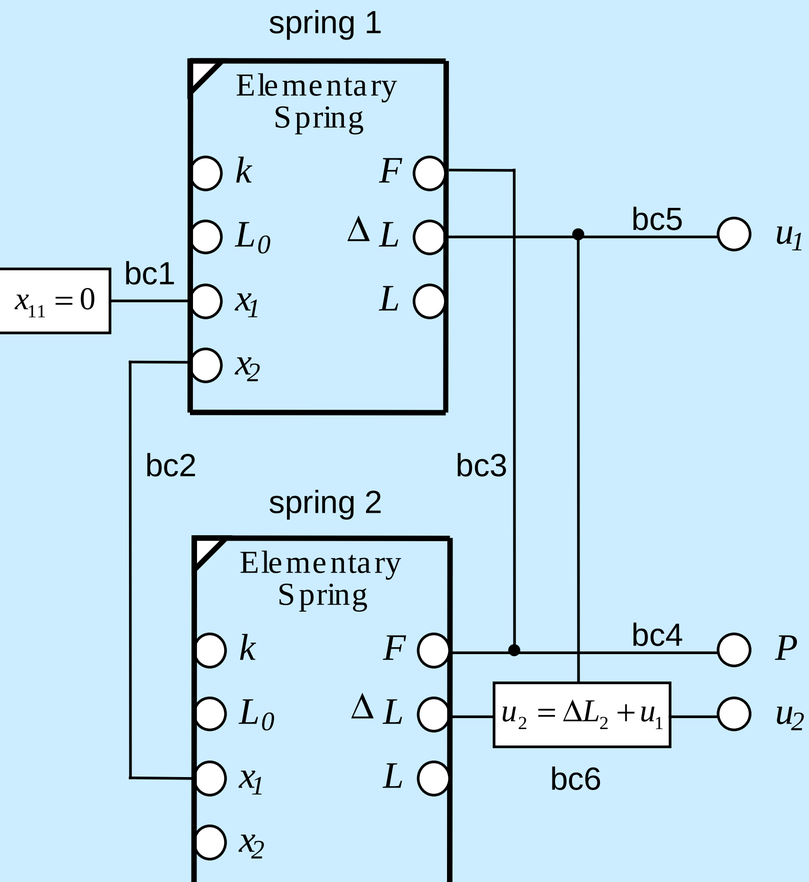
```
COB spring SUBTYPE_OF abb;
   undeformed_length, L<sub>0</sub> : REAL;
   spring_constant, k : REAL;
   start, x<sub>1</sub> : REAL;
   end, x<sub>2</sub> : REAL;
   length, L : REAL;
   total_elongation, &Delta;L : REAL;
   force, F : REAL;
 RELATIONS
   r1 : "<length> == <end> - <start>";
   r2 : "<total_elongation> == <length> - <undeformed_length>";
   r3 : "<force> == <spring_constant> * <total_elongation>";
END_COB;
```

COBs as Building Blocks

Two Spring System



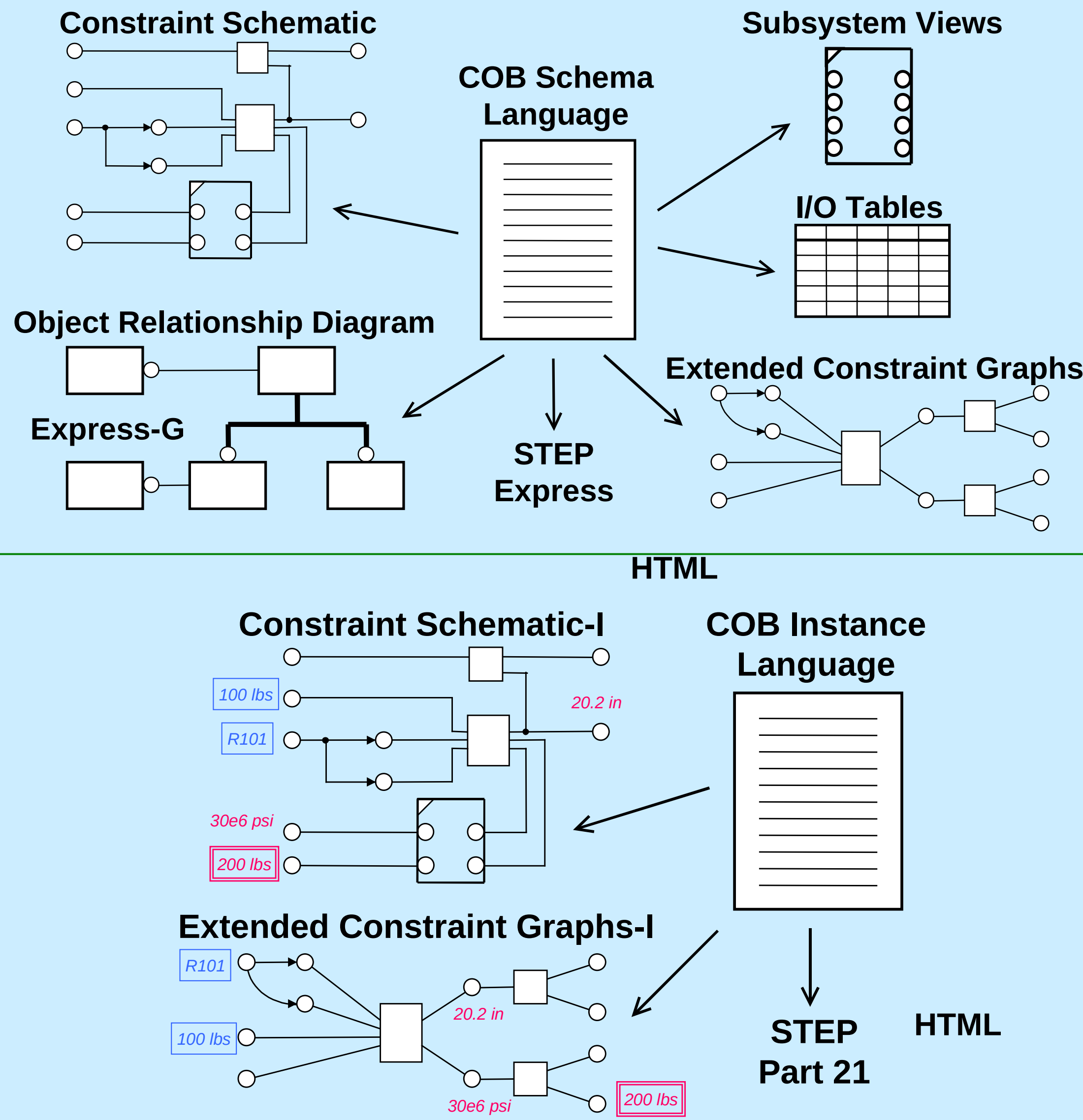
Constraint Schematic



Lexical COB Schema Template

```
COB spring_system SUBTYPE_OF analysis_system;
   spring1 : spring;
   spring2 : spring;
   deformation1, u<sub>1</sub> : REAL;
   deformation2, u<sub>2</sub> : REAL;
   load, P : REAL;
 RELATIONS
   bc1 : "<spring1.start> == 0.0";
   bc2 : "<spring1.end> == <spring2.start>";
   bc3 : "<spring1.force> == <spring2.force>";
   bc4 : "<spring2.force> == <load>";
   bc5 : "<deformation1> == <spring1.total_elongation>";
   bc6 : "<deformation2> == <spring2.total_elongation>
            + <deformation1>";
END_COB;
```

COB Modeling Views

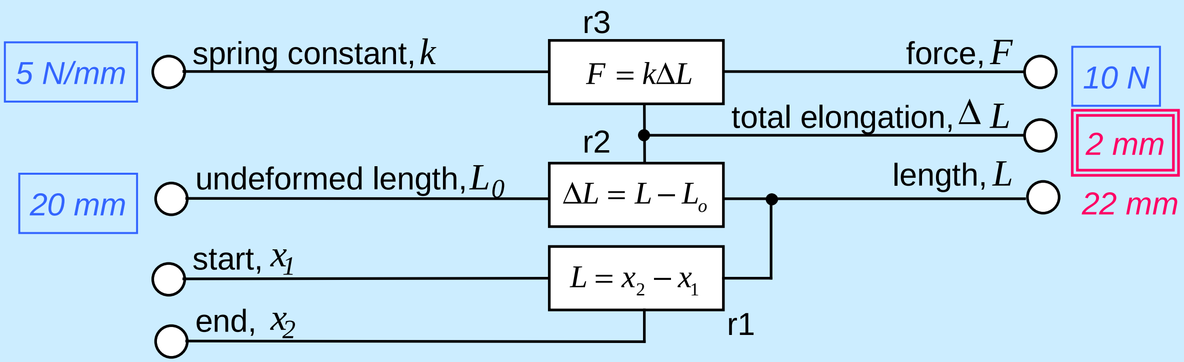


Example COB Instance

Spring Primitive

Constraint Schematic Instance Views

example 1, state 1



Lexical COB Instances

input:

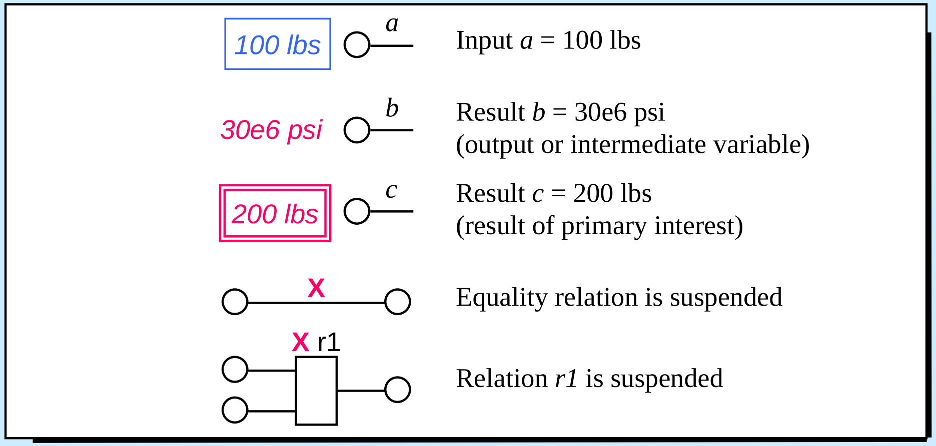
```
INSTANCE_OF spring;
   undeformed_length : 20.0;
   spring_constant : 5.0;
   start : ?;
   end : ?;
   length : ?;
   total_elongation : ?;
   force : 10.0;
END_INSTANCE;
```

result (reconciled):

```
INSTANCE_OF spring;
   undeformed_length : 20.0;
   spring_constant : 5.0;
   start : ?;
   end : ?;
   length : 22.0;
   total_elongation : 2.0;
   force : 10.0;
END_INSTANCE;
```

Basic Constraint Schematic Notation

Instances

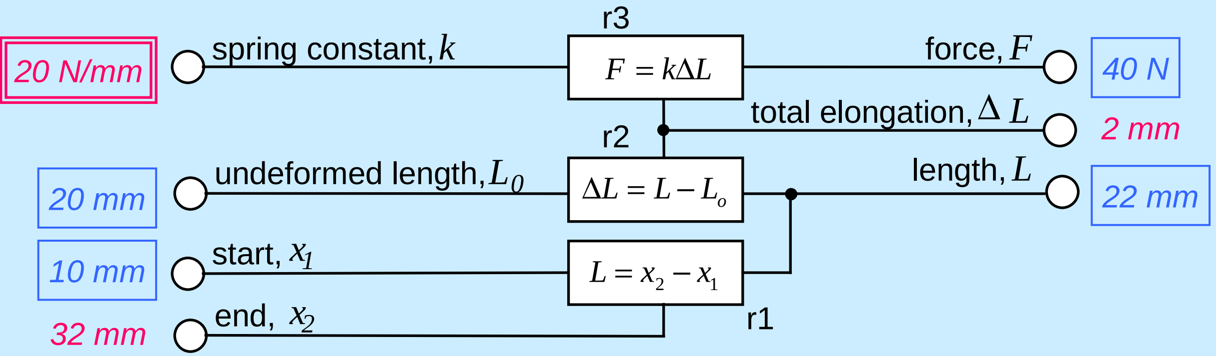


Multidirectional I/O

Spring Primitive

Constraint Schematic Instance View

example 1, state 5



Lexical COB Instance

```
input:

INSTANCE_OF spring;
   undeformed_length : 20.0;
   spring_constant : ?;
   start : 10.0;
   end : ?;
   length : 22.0;
   total_elongation : ?;
   force : 40.0;
END_INSTANCE;


result:

INSTANCE_OF spring;
   undeformed_length : 20.0;
   spring_constant : 20.0;
   start : 10.0;
   end : 32.0;
   length : 22.0;
   total_elongation : 2.0;
   force : 40.0;
END_INSTANCE;
```

Spring Examples Implemented in *XaiTools* X-Analysis Integration Toolkit

spring

Name	Symbol	Type	Input	Values
root		spring		
undeformed_length	L₀	REAL	Input	20
spring_constant	k	REAL	Input	5
start	x₁	REAL	Output	No value
end0	x₂	REAL	Output	No value
length	L	REAL	Output	22
total_elongation	ΔL	REAL	Output	2
force	F	REAL	Input	10

Solve

root (spring)

Name	Local	Oneway	Relation	Active
r1	Y		<length> == <end0> - <start>	✓
r2	Y		<total_elongation> == <length> - <undeformed_length>	✓
r3	Y		<force> == <spring_constant> * <total_elongation>	✓

spring

Name	Symbol	Type	Input	Values
root		spring		
undeformed_length	L₀	REAL	Input	20
spring_constant	k	REAL	Output	20
start	x₁	REAL	Input	10
end0	x₂	REAL	Output	32
length	L	REAL	Input	22
total_elongation	ΔL	REAL	Output	2
force	F	REAL	Input	40

Solve

root (spring)

Name	Local	Oneway	Relation	Active
r1	Y		<length> == <end0> - <start>	✓
r2	Y		<total_elongation> == <length> - <undeformed_length>	✓
r3	Y		<force> == <spring_constant> * <total_elongation>	✓

spring_system

Name	Symbol	Type	Input	Values
root		spring_system		
spring1		spring		
undeformed_length	L₀	REAL	Input	8
spring_constant	k	REAL	Input	5
start	x₁	REAL	Output	0
end0	x₂	REAL	Output	10
length	L	REAL	Output	10
total_elongation	ΔL	REAL	Output	2
force	F	REAL	Output	10
spring2		spring		
undeformed_length	L₀	REAL	Input	8
spring_constant	k	REAL	Input	20
start	x₁	REAL	Output	10
end0	x₂	REAL	Output	18.5
length	L	REAL	Output	8.5
total_elongation	ΔL	REAL	Output	0.5
force	F	REAL	Output	10
deformation1	u₁	REAL	Output	2
deformation2	u₂	REAL	Output	2.5
load	P	REAL	Input	10

Solve

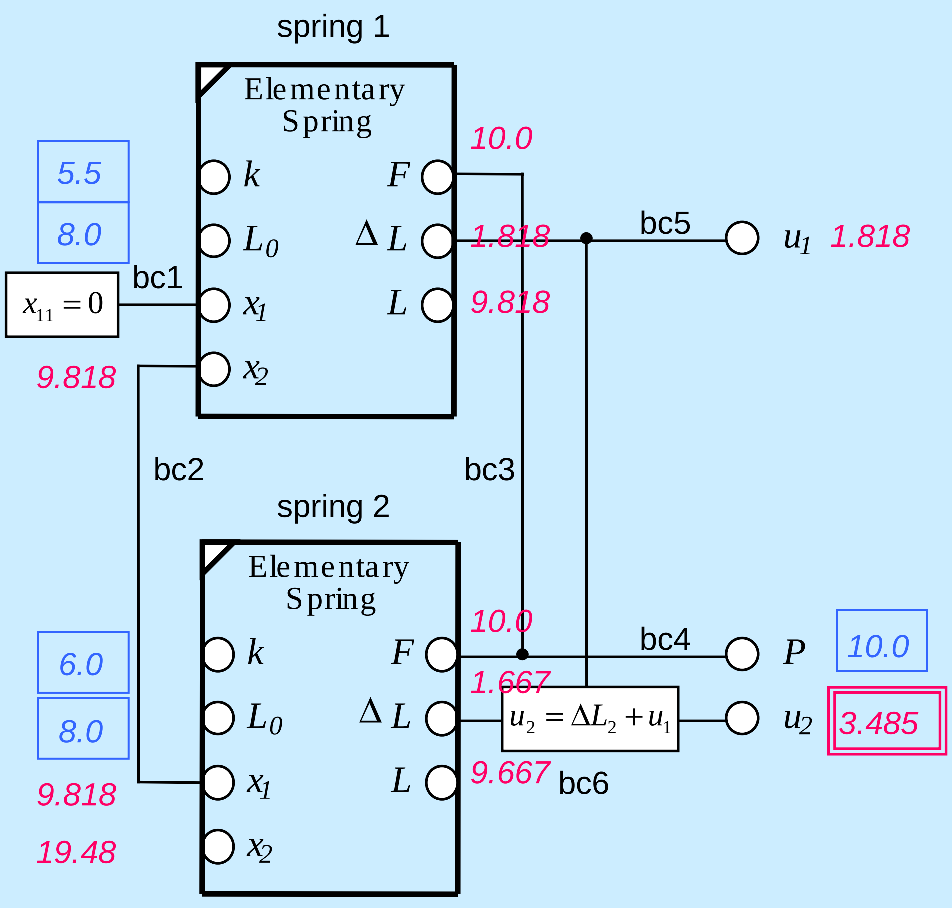
root (spring_system)

Name	Local	Oneway	Relation	Active
r1	Y		<spring1.start> == 0.0	✓
r2	Y		<spring1.end0> == <spring2.start>	✓
r3	Y		<spring1.force> == <spring2.force>	✓
r4	Y		<spring2.force> == <load>	✓
r5	Y		<deformation1> == <spring1.total_elongation>	✓
r6	Y		<deformation2> == <spring2.total_elongation> + <deformation1>	✓

Analysis System Instance

Two Spring System

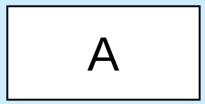
Constraint Schematic Instance View



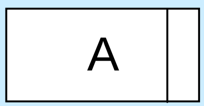
Lexical COB Instance

```
input:
INSTANCE_OF spring_system;
   spring1.undeformed_length : 8.0;
   spring1.spring_constant : 5.5;
   spring2.undeformed_length : 8.0;
   spring2.spring_constant : 6.0;
   load : 10.0;
END_INSTANCE;

result:
INSTANCE_OF spring_system;
   spring1.undeformed_length : 8.0;
   spring1.spring_constant : 5.5;
   spring1.start : 0.0;
   spring1.end0 : 9.81818181818182;
   spring1.force : 10.0;
   spring1.total_elongation : 1.81818181818181818;
   spring1.length : 9.81818181818182;
   spring2.undeformed_length : 8.0;
   spring2.spring_constant : 6.0;
   spring2.start : 9.81818181818182;
   spring2.force : 10.0;
   spring2.total_elongation : 1.66666666666666;
   spring2.length : 9.66666666666667;
   spring2.end0 : 19.48484848484848;
   load : 10.0;
   deformation1 : 1.81818181818181818;
   deformation2 : 3.48484848484848484;
END_INSTANCE;
```

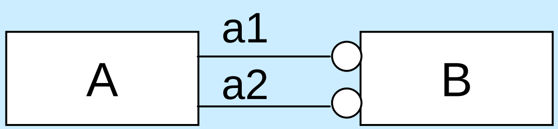
Basic EXPRESS-G notation



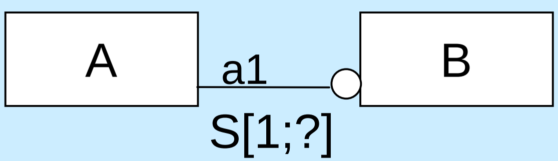
A is an entity (class)
Instance of A are objects



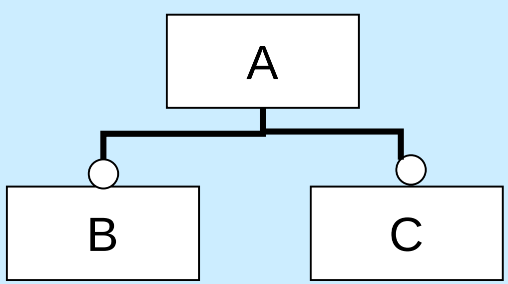
A is a simple type
(BOOLEAN, LOGICAL, BINARY, NUMBER, INTEGER, REAL, STRING)



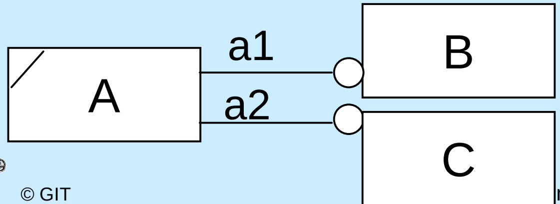
A has two attribute, a1 and a2, that are both type B



A has an attribute, a1, that is a Set of 1 or ore entities of type B

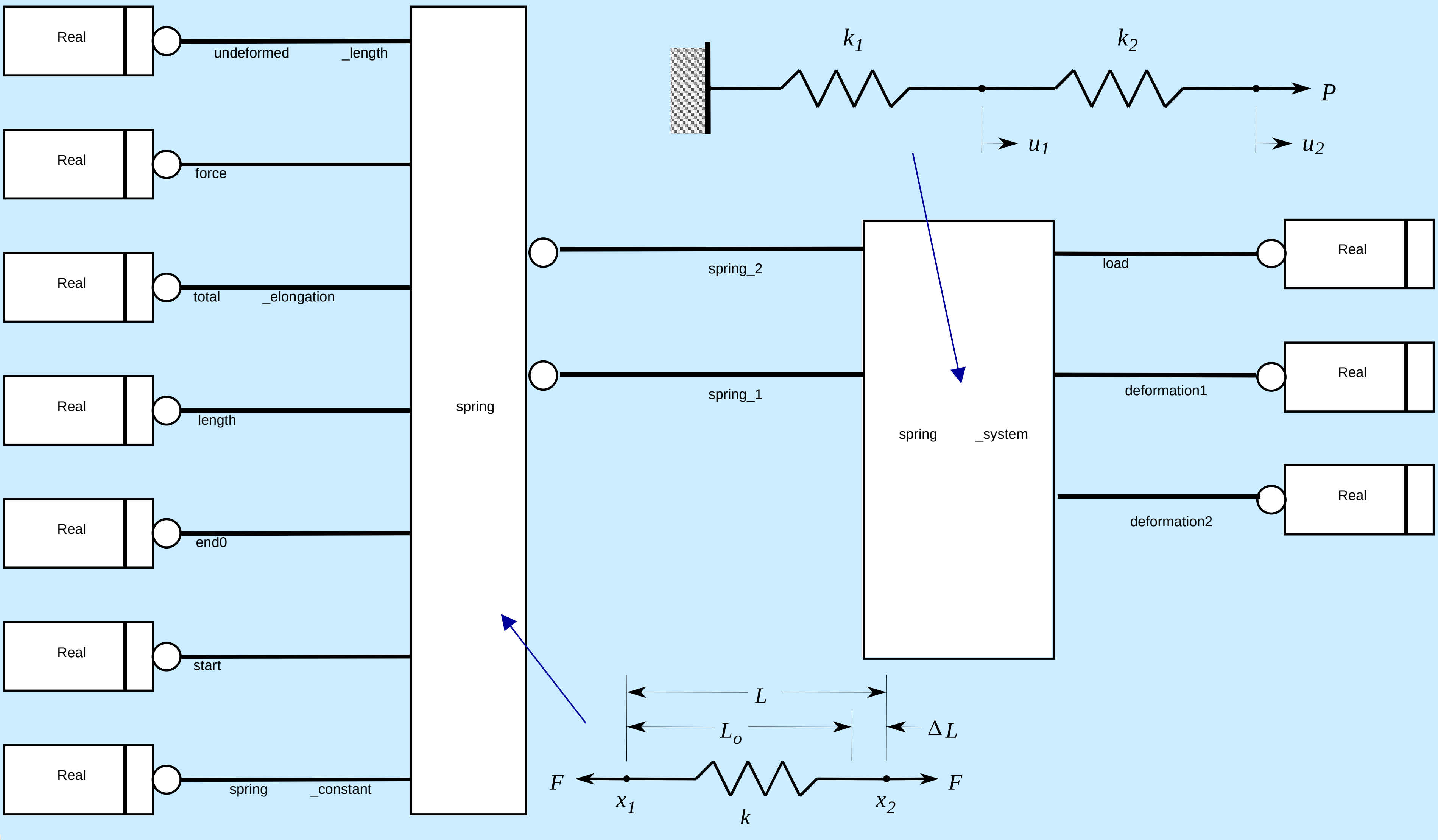


A is a supertype of B and C.
(B and C are subtype of A)



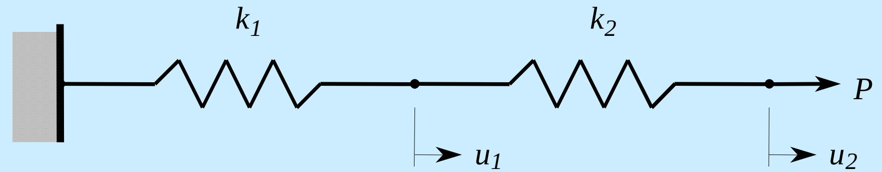
Unofficial extensions:
A has two levels, a1 and a2.
a1 is type B. a2 is type C.

COB Object Model View (EXPRESS-G) Spring Schema



Declarative Knowledge / Derivable Behavior

Two Spring System



$r_{11} : L_1 = x_{12} - x_{11}$

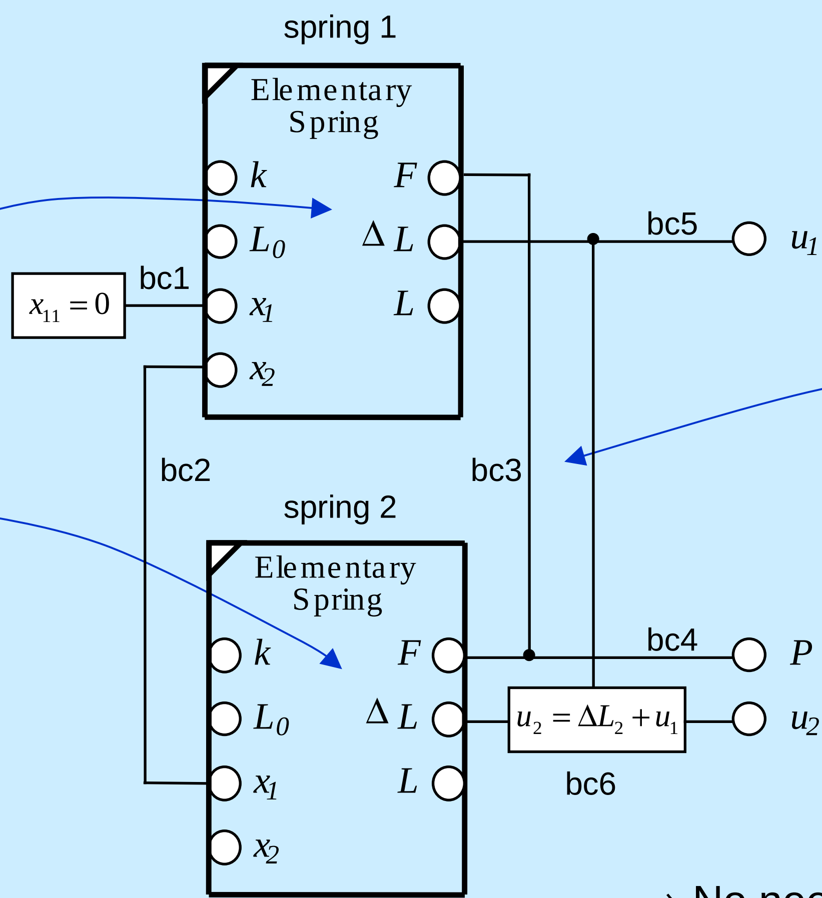
$r_{12} : \Delta L_1 = L_1 - L_{10}$

$r_{13} : F_1 = k_1 \Delta L_1$

$r_{21} : L_2 = x_{22} - x_{21}$

$r_{22} : \Delta L_2 = L_2 - L_{20}$

$r_{23} : F_2 = k_2 \Delta L_2$



$bc_1 : x_{11} = 0$

$bc_2 : x_{12} = x_{21}$

$bc_3 : F_1 = F_2$

$bc_4 : F_2 = P$

$bc_5 : u_1 = \Delta L_1$

$bc_6 : u_2 = \Delta L_2 + u_1$

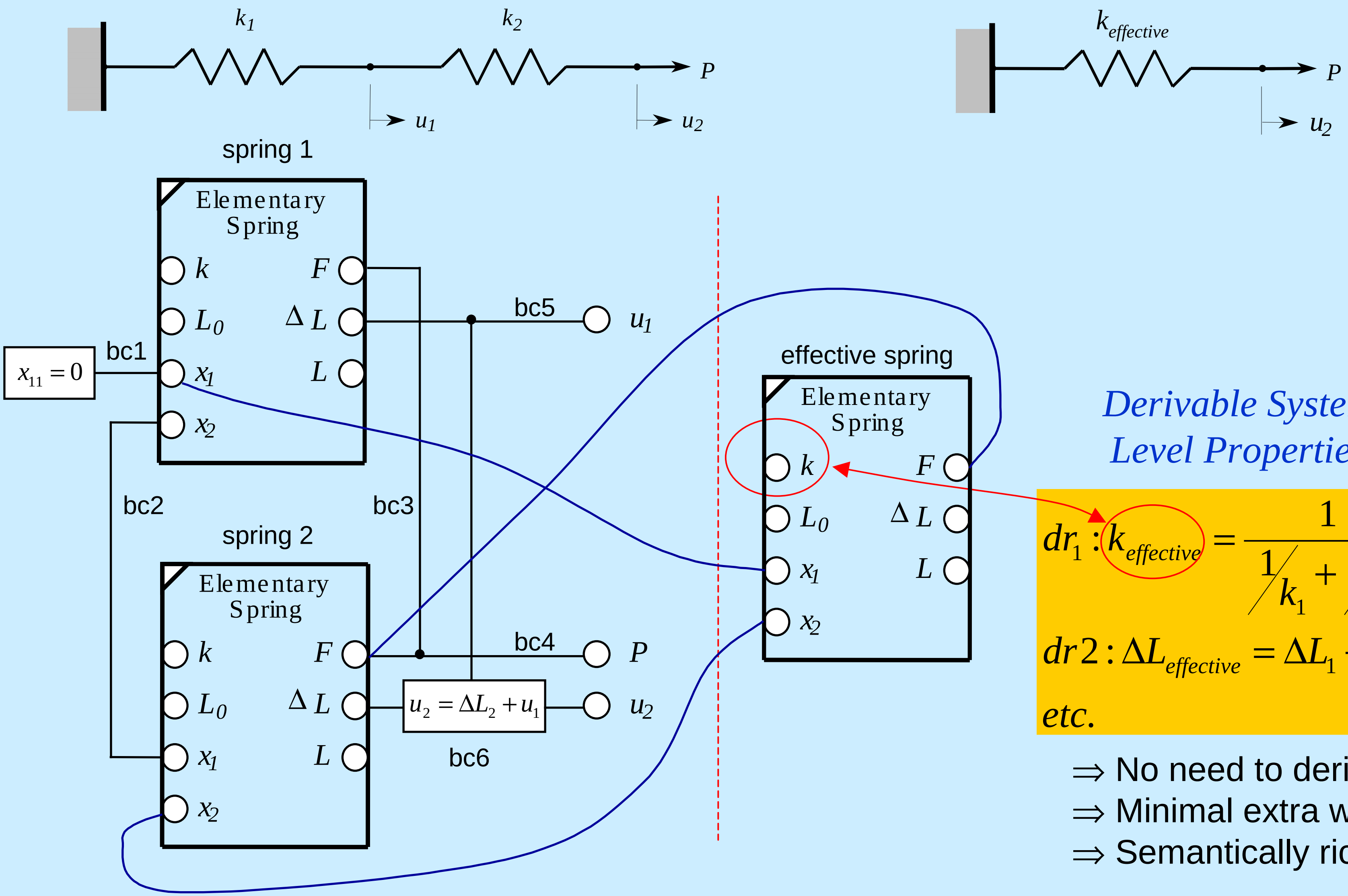
Derivable Behavior

$$dr_1 : u_1 = \frac{P}{k_1}$$

$$dr_2 : u_2 = P \frac{k_1 + k_2}{k_1 k_2}$$

$\Rightarrow$ No need to include explicitly (redundant)

Achieving Effective System Properties via Semantically Rich COBs



Derivable System Level Properties

$$dr_1 : k_{effective} = \frac{1}{1/k_1 + 1/k_2}$$

$$dr2 : \Delta L_{effective} = \Delta L_1 + \Delta L_2$$

etc.

⇒ No need to derive
⇒ Minimal extra work
⇒ Semantically richer

Constrained Object Language (COBs)

- Capabilities & features
  - Various forms: computable lexical form, graphical form, etc.
  - Sub/supertypes, basic aggregates, multifidelity objects
  - Multidirectionality (I/O change)
  - Wrapping external programs as black box relations
- Analysis module/template applications:
  - Product model idealizations
  - Explicit associativity relations with design models & other analyses
  - Black box reuse of existing tools (e.g., FEA tools, in-house functions)
  - Reusable, adaptable analysis building blocks
  - Synthesis (sizing) and verification (analysis)

Constrained Object Language (cont.)

- Summary
  - Declarative knowledge representation combining objects & constraints
  - COBs = (STEP EXPRESS subset) + (constraint concepts & views)
  - Advantages over traditional representations:
    - » Greater solution control
    - » Richer semantics (e.g., equations wrapped in engineering context)
    - » Capture of reusable knowledge

Outline

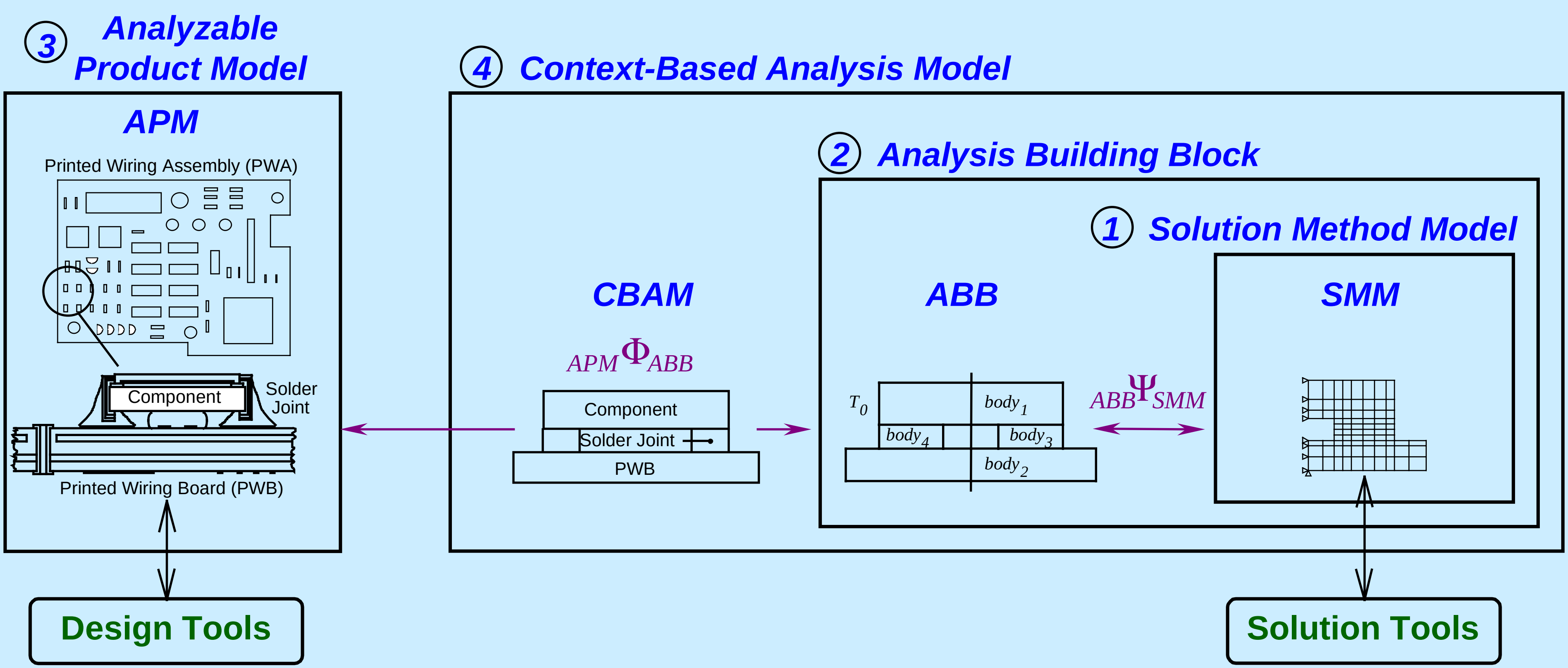
- Analysis Integration Challenges
- Introduction to Constrained Objects (COBs)
- Overview of COB-based XAI ⬅
- Example Applications
  - Electronic Packaging Thermomechanical Analysis
  - Aerospace Structural Analysis
- Summary

Components of the MRA Analysis Integration Technique

- Conceptual architecture: MRA
- Methodology
- General purpose MRA toolkit: *XaiTools*
  - Toolkit architecture
  - Users guide
  - Tutorials (work-in-process)
- Product/company-specific applications
  - PWA/Bs (ProAM)
  - Aerospace structural analysis (Boeing PSI)
  - Chip packaging/mounting (Shinko)

See http://eislab.gatech.edu/ for references

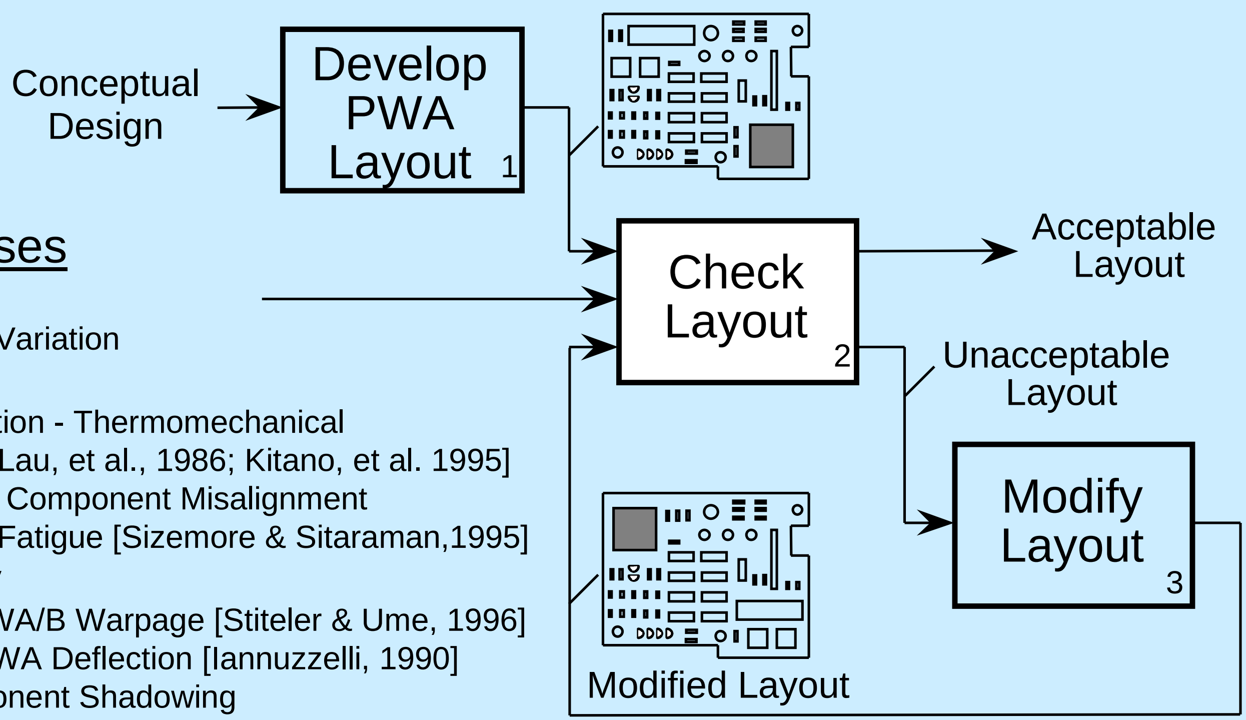
Multi-Representation Architecture for Design-Analysis Integration



- Composed of four representations (information models)
- Provides flexible, modular mapping between design & analysis models
- Creates automated, product-specific analysis modules (CBAMs)
- Represents design-analysis associativity explicitly

Routine Analysis: Opportunity for Automation

Typical PWA Design Process



<u>Routine Analyses</u>

Performance

EMI - Trace Spacing Variation

Reliability

Solder Joint Deformation - Thermomechanical
[Engelmaier, 1989; Lau, et al., 1986; Kitano, et al. 1995]

Solder Joint Fatigue - Component Misalignment

Plated Through-Hole Fatigue [Sizemore & Sitaraman,1995]

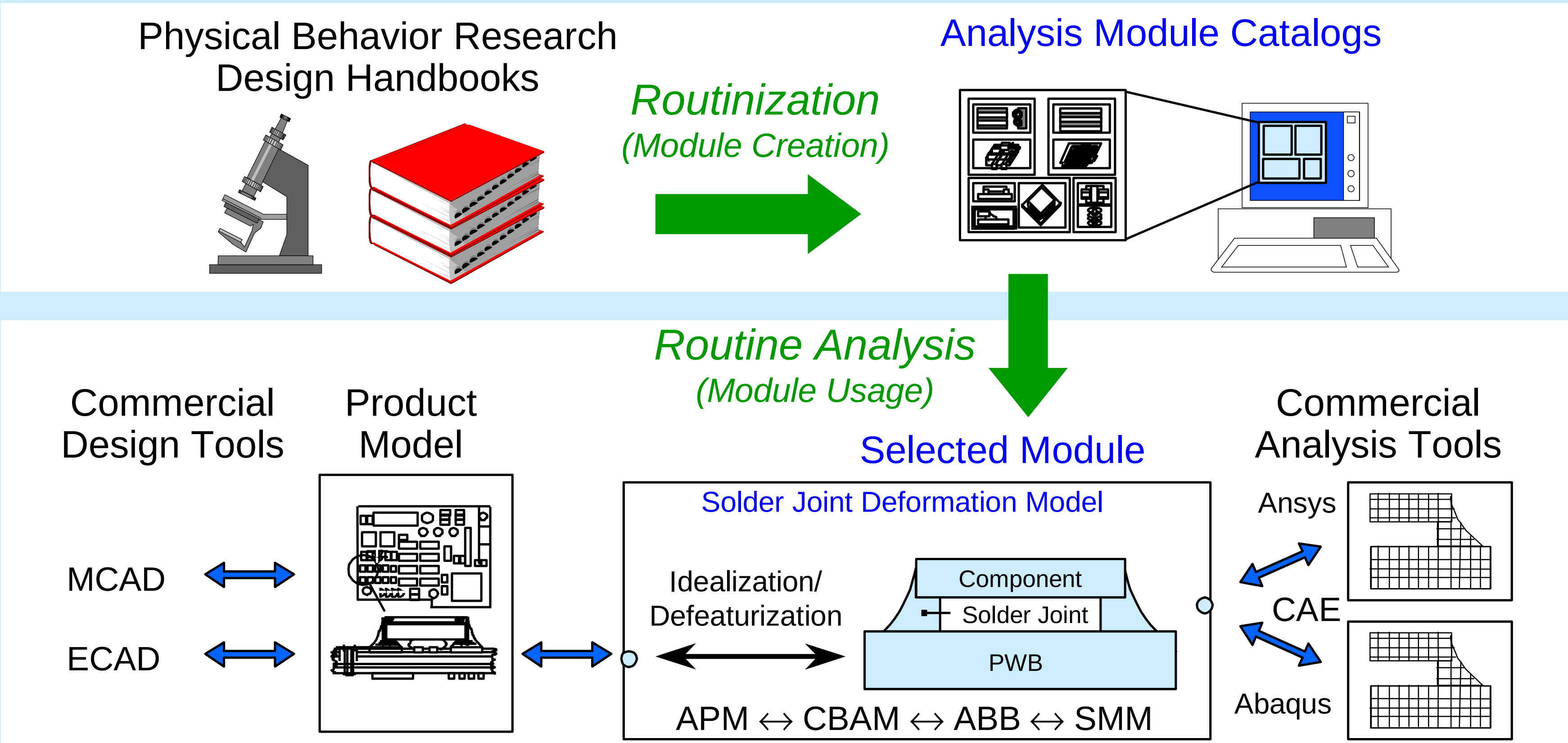
Manufacturability

Reflow Soldering - PWA/B Warpage [Stiteler & Ume, 1996]

Bed-of-Nails Test - PWA Deflection [Iannuzzelli, 1990]

Solder Wave - Component Shadowing

Design-Analysis Integration Methodology



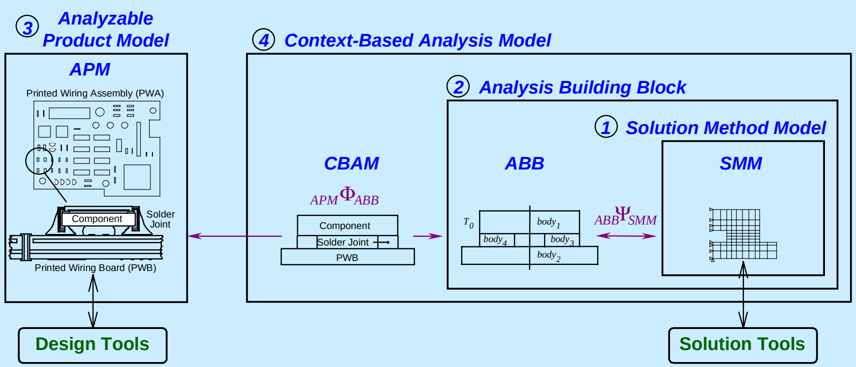
- Provides technique to bridge CAD-CAE gap
- Uses AI & info. technology: objects, constraints, STEP

XaiTools

Prototype X-Analysis Integration Toolkit

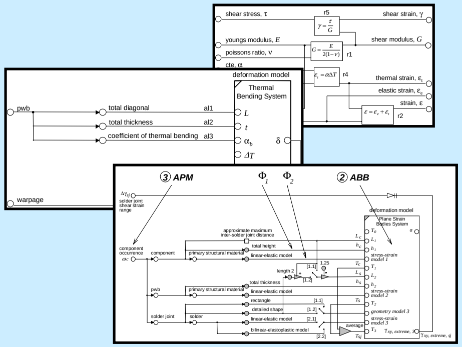
Second Generation - Java-based

Multi-Representation Architecture (MRA)

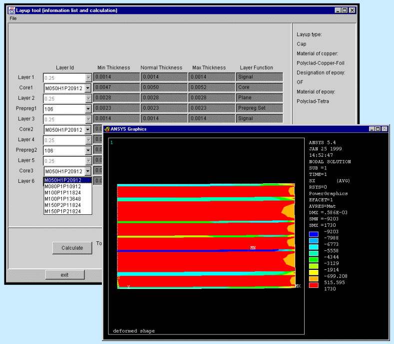


Analysis Modules & Building Blocks

Constraint Schematics



Implementations

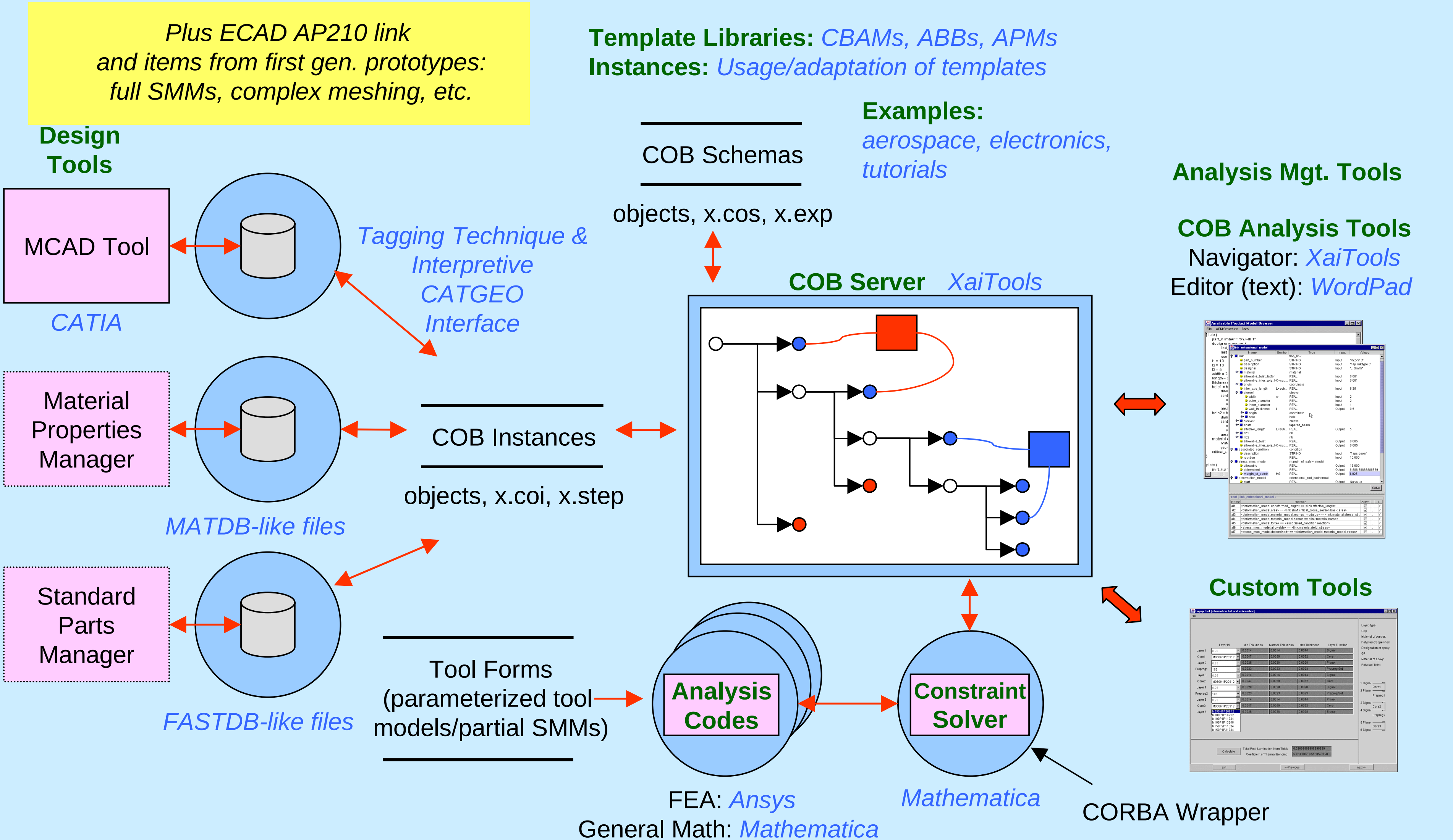


- Product-independent MRA toolkit
- Lexical constrained objects (COBs)
  - Data-driven creation
  - User-adaptable
- Mathematica constraint solver
  - More capabilities
- SMM-type wrappings:
  - FEA tools: Ansys, Abaqus*
  - Symbolic Eqn. Solver: Mathematica
- Extended APM technique for design links:
  - CATIA MCAD modeler
- Updates/Extensions in progress*:
  - PWB/A: GenCAM; STEP AP210-based APM link w/ Mentor Graphics BoardStation
  - Generalized MCAD modeler links
  - Advanced parametric FEA transformation
  - Object-Oriented Optimization
  - CORBA-based tool interchanges
  - XML views of analysis results etc.

XaiTools Tool Architecture

Company/Product-Independent View

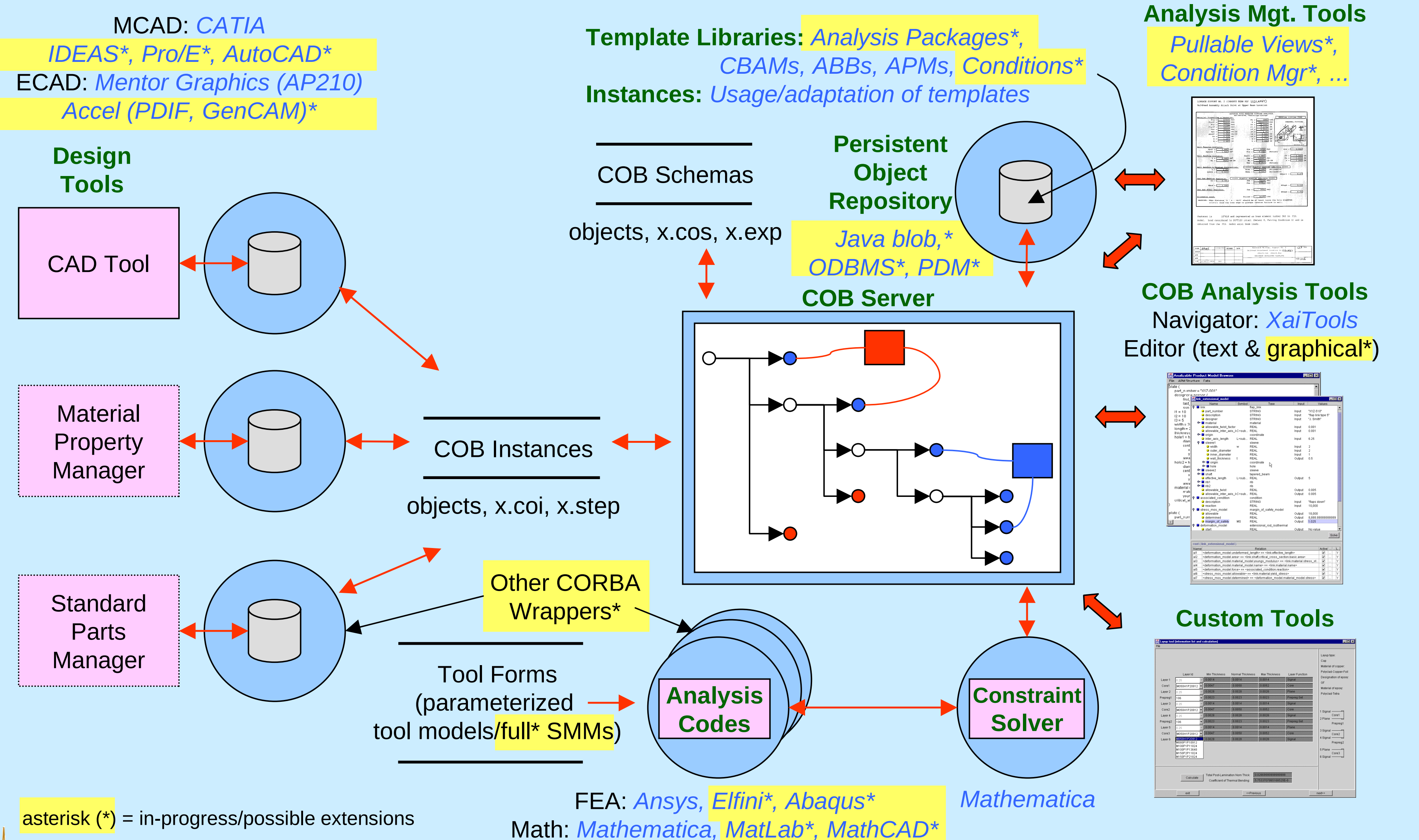
Capabilities as of 12/98



XaiTools Tool Architecture

Company/Product-Independent View

In-Progress & Potential Extensions as of 6/99



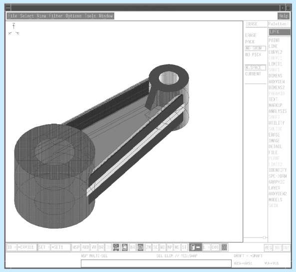
asterisk (*) = in-progress/possible extensions

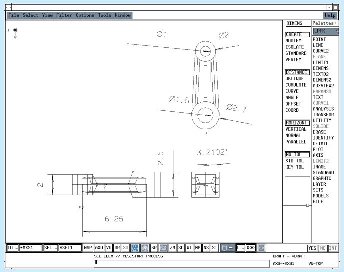
Flexible High Diversity Design-Analysis Integration

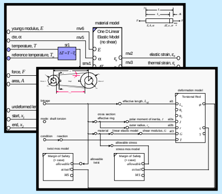
Tutorial Examples: Flap Link (Mechanical/Structural Analysis)

MCAD Tools

CATIA



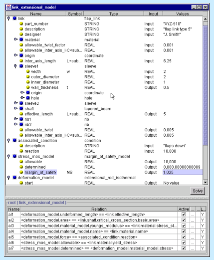




Modular, Reusable Template Libraries

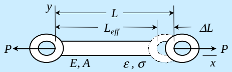
Analysis Modules (CBAMs) of Diverse Mode & *Fidelity*

XaiTools



Analysis Tools

General Math *Mathematica*

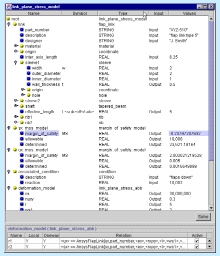


Extension

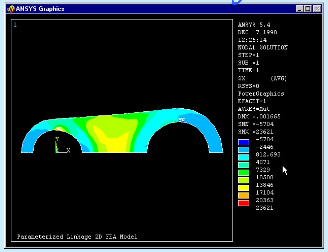
1D, 2D, 3D*

Analyzable Product Model

XaiTools



FEA *Ansys*

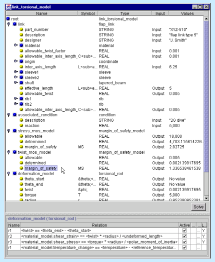


Materials DB

MATDB-like

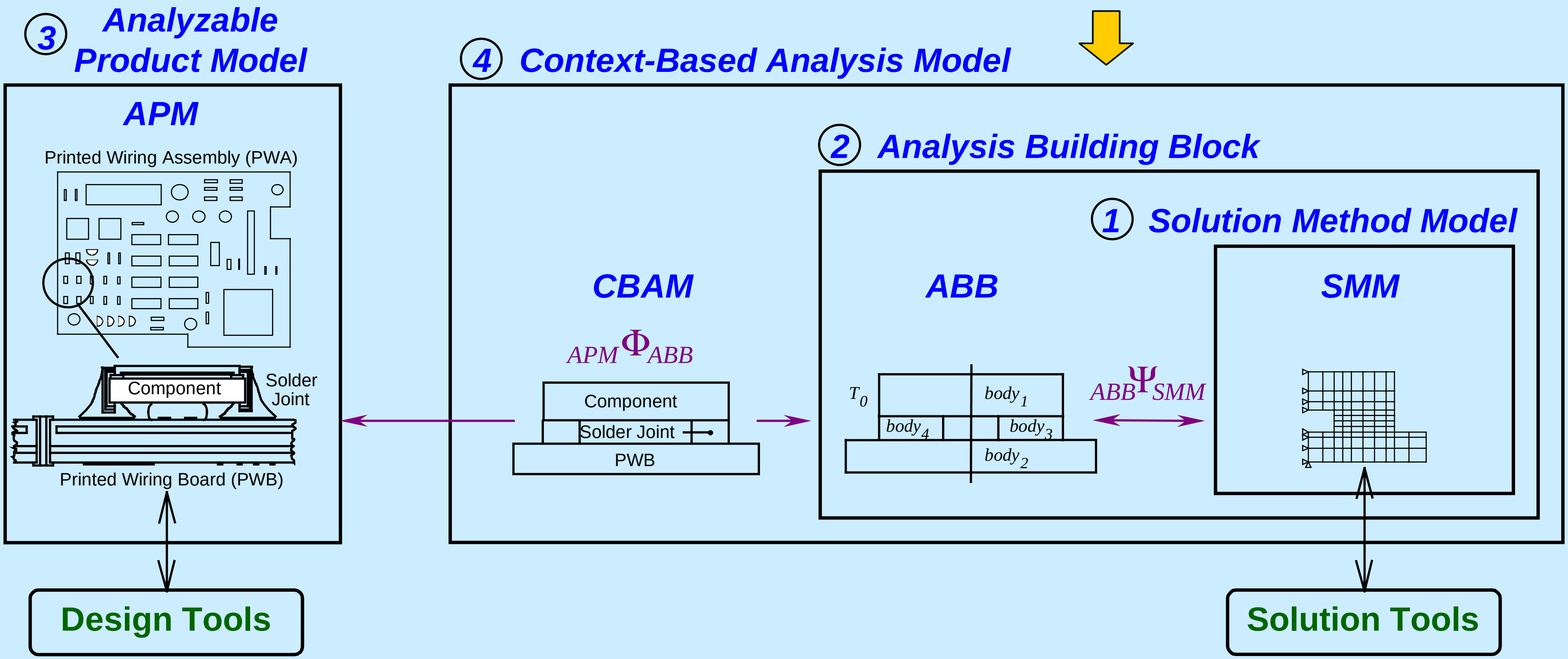
Torsion

1D



* = Item not available in working prototype yet (all others have working examples)

Multi-Representation Architecture for Design-Analysis Integration



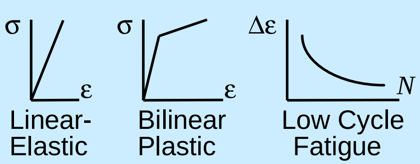
Analysis Building Blocks (ABBs)

Object representation of product-independent analytical engineering concepts

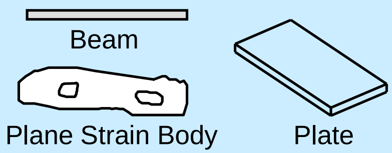
Analysis Primitives

- Primitive building blocks

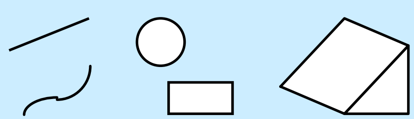
Material Models



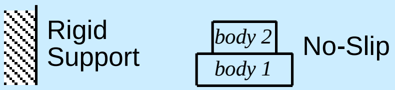
Continua



Geometry

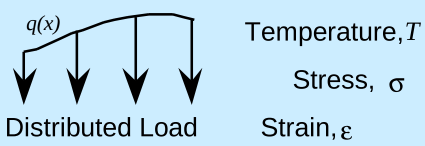


Interconnections



Discrete Elements

Analysis Variables

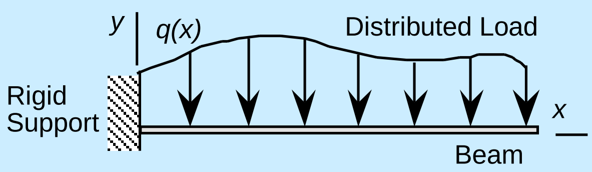


Analysis Systems

- Containers of ABB "assemblies"

Specialized

- Predefined templates



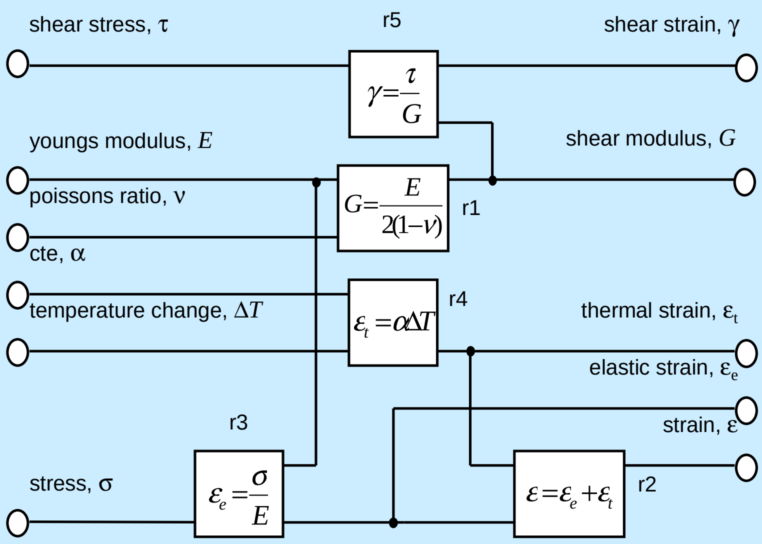
Cantilever Beam System

General

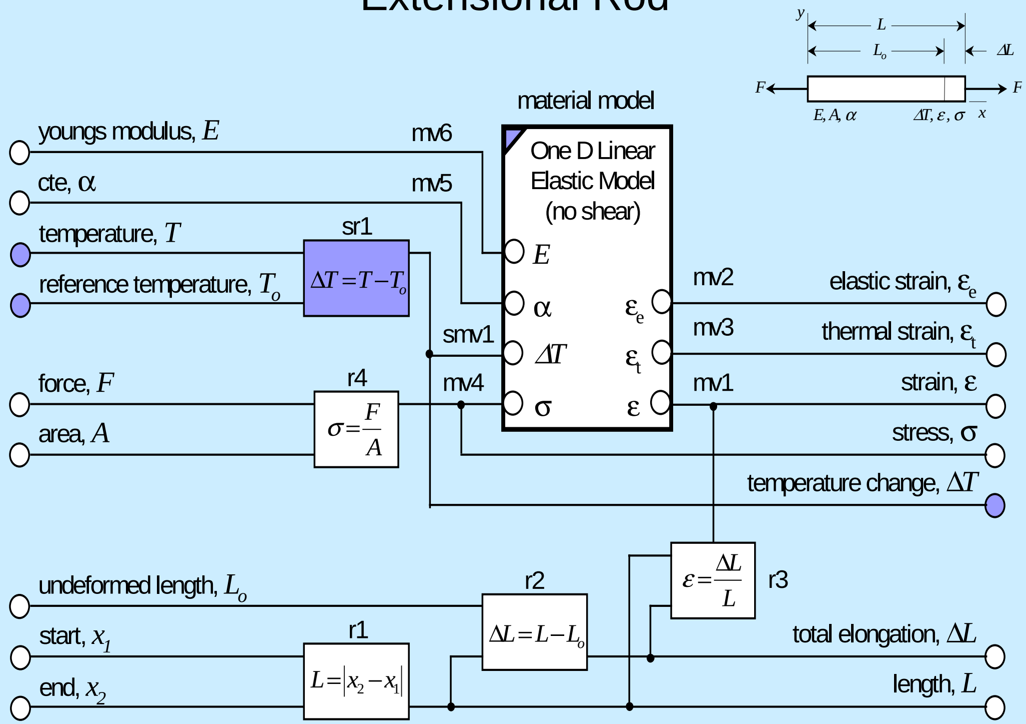
- User-defined systems

Primitive ABBs

1D Linear Elastic Model

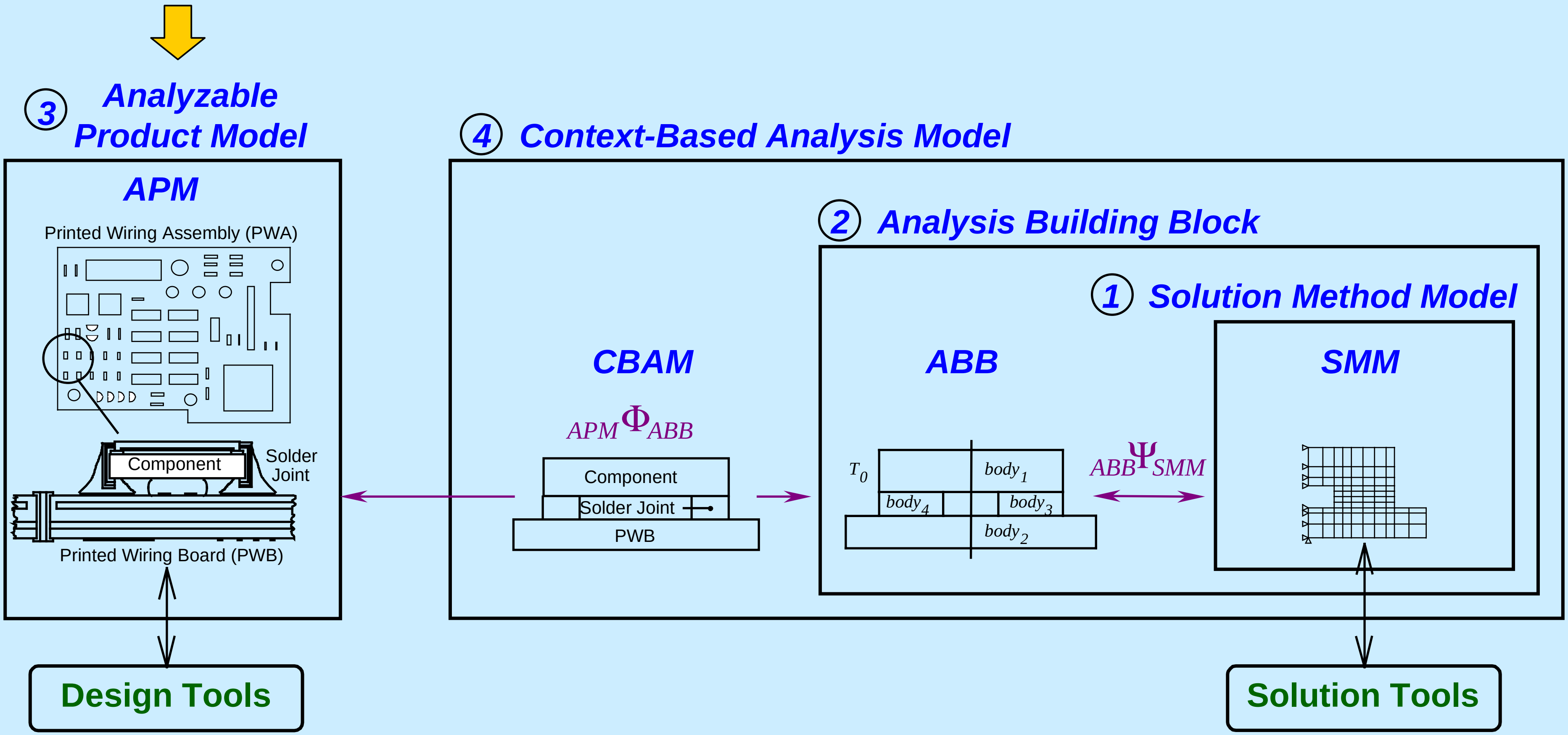


Extensional Rod



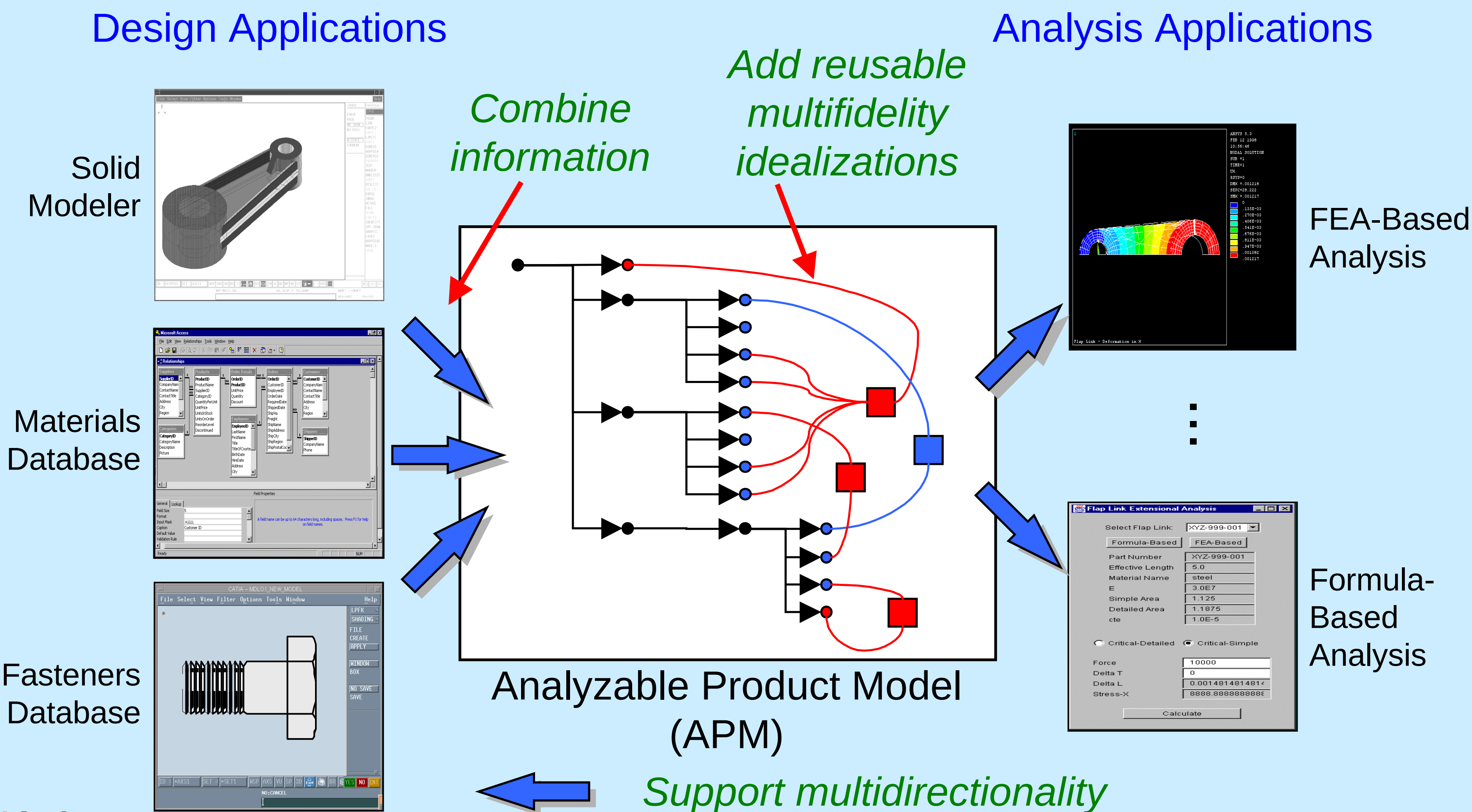
Usage by Flap Link Model

Multi-Representation Architecture for Design-Analysis Integration



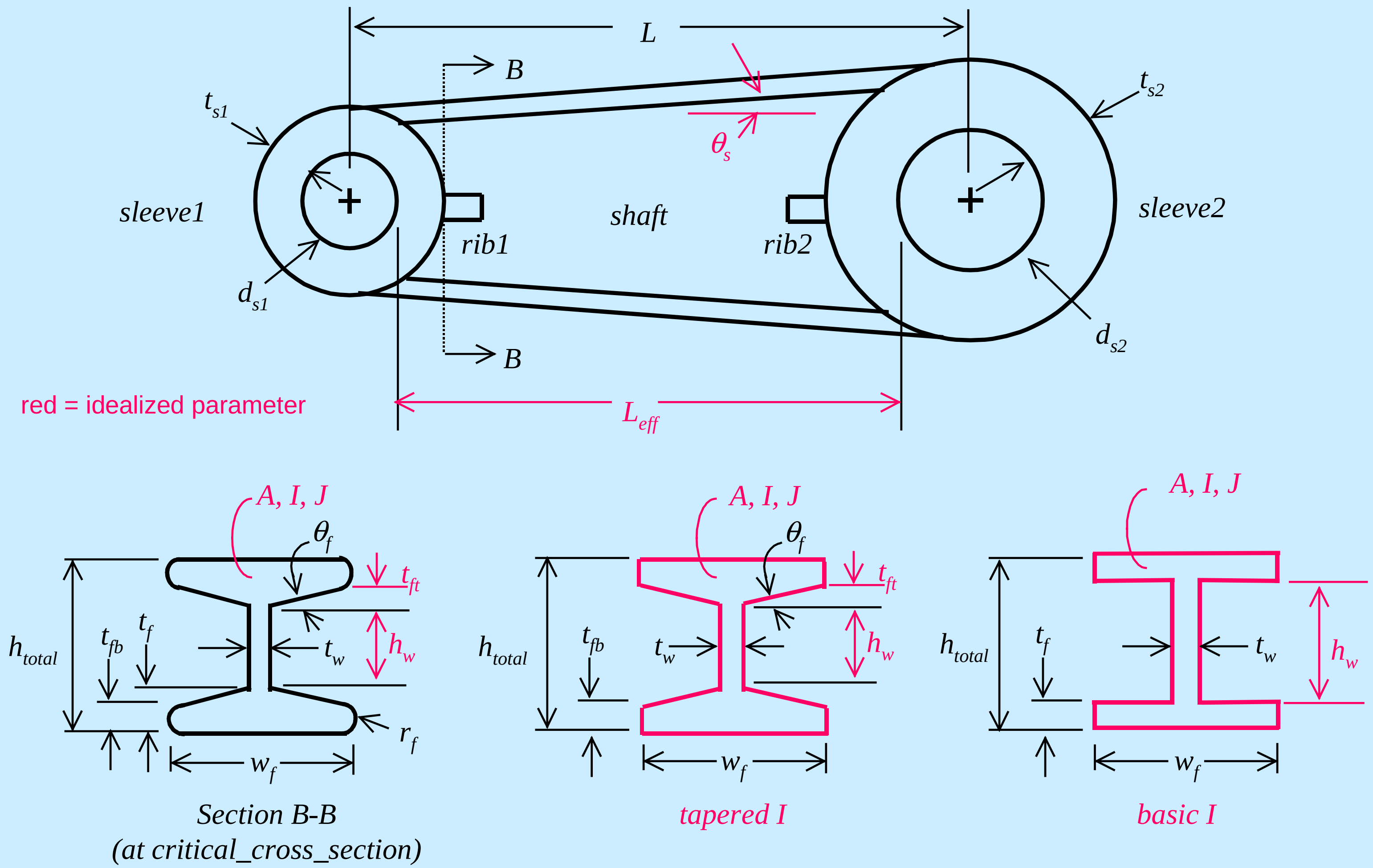
Analyzable Product Models (APMs)

Provide advanced access to design data needed by diverse analyses.



Flap Link Geometric Model

(with idealizations)

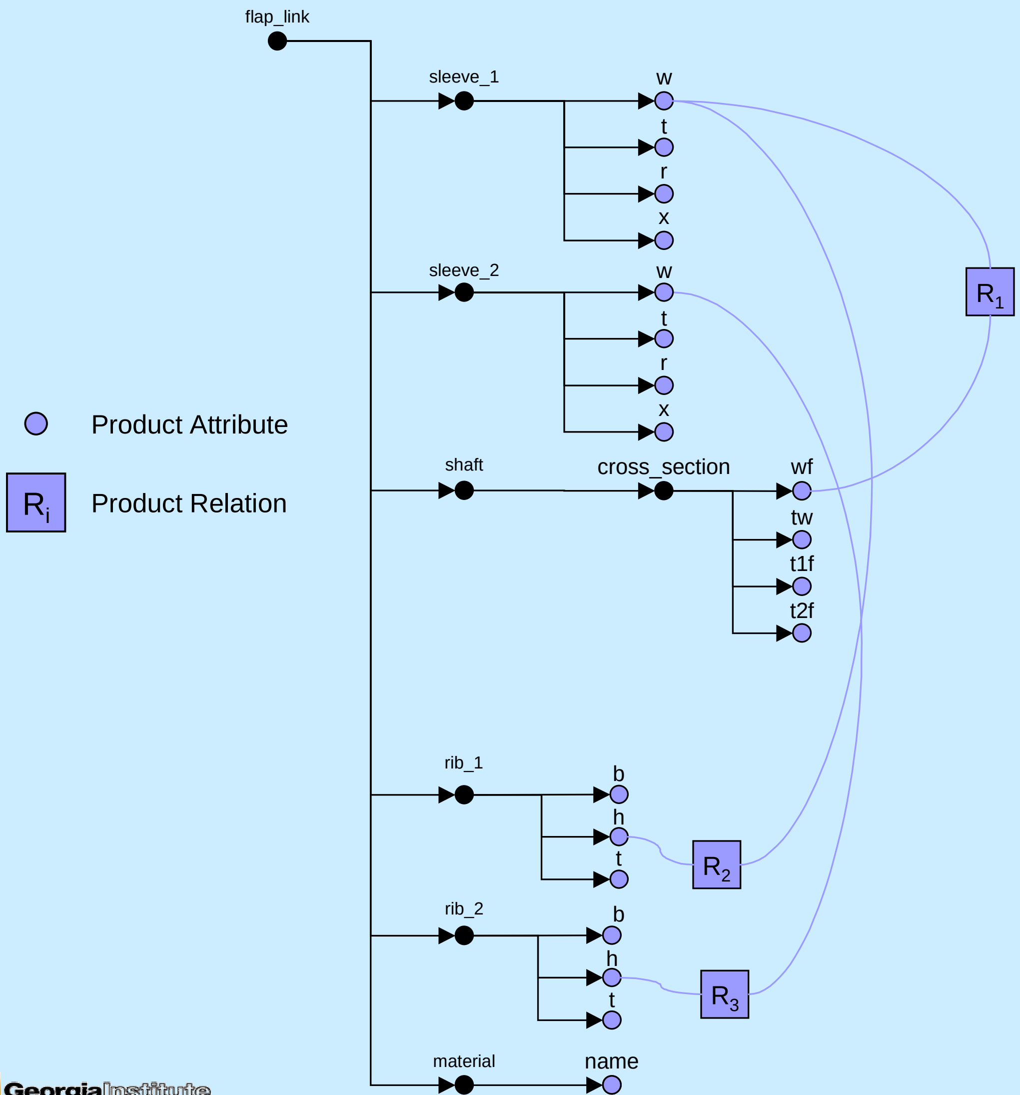


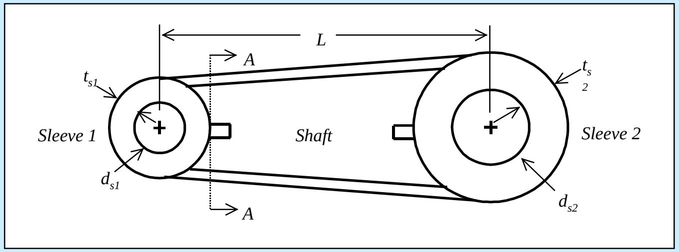
Detailed Design

Multifidelity Idealizations

Flap Linkage Example

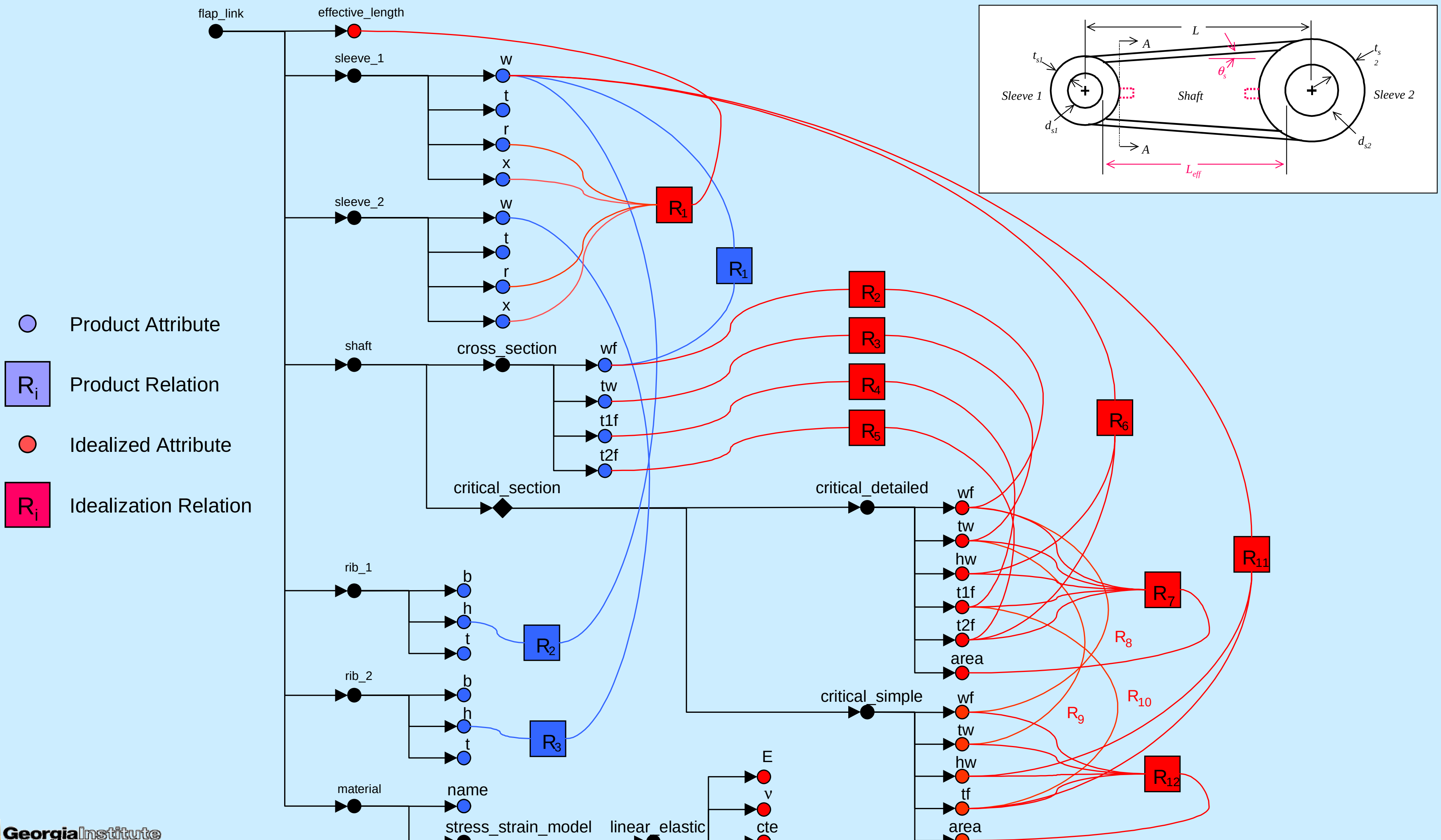
Manufacturable Product Model (MPM) = Design Description





Flap Linkage Example

Analyzable Product Model (APM) = MPM Subset + Idealizations



APM Interface with Tagged CAD Models

1) APM COB Tool

7) Solve idealizations
8) Use in analysis

2) request

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

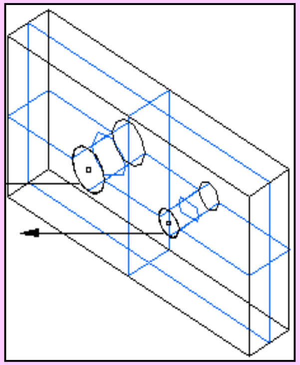
COB instance format

3) GIT Interface program

4) *tk/tcl CATGEO wrapper*

3 and 4 assumed replaceable by CNext

5)



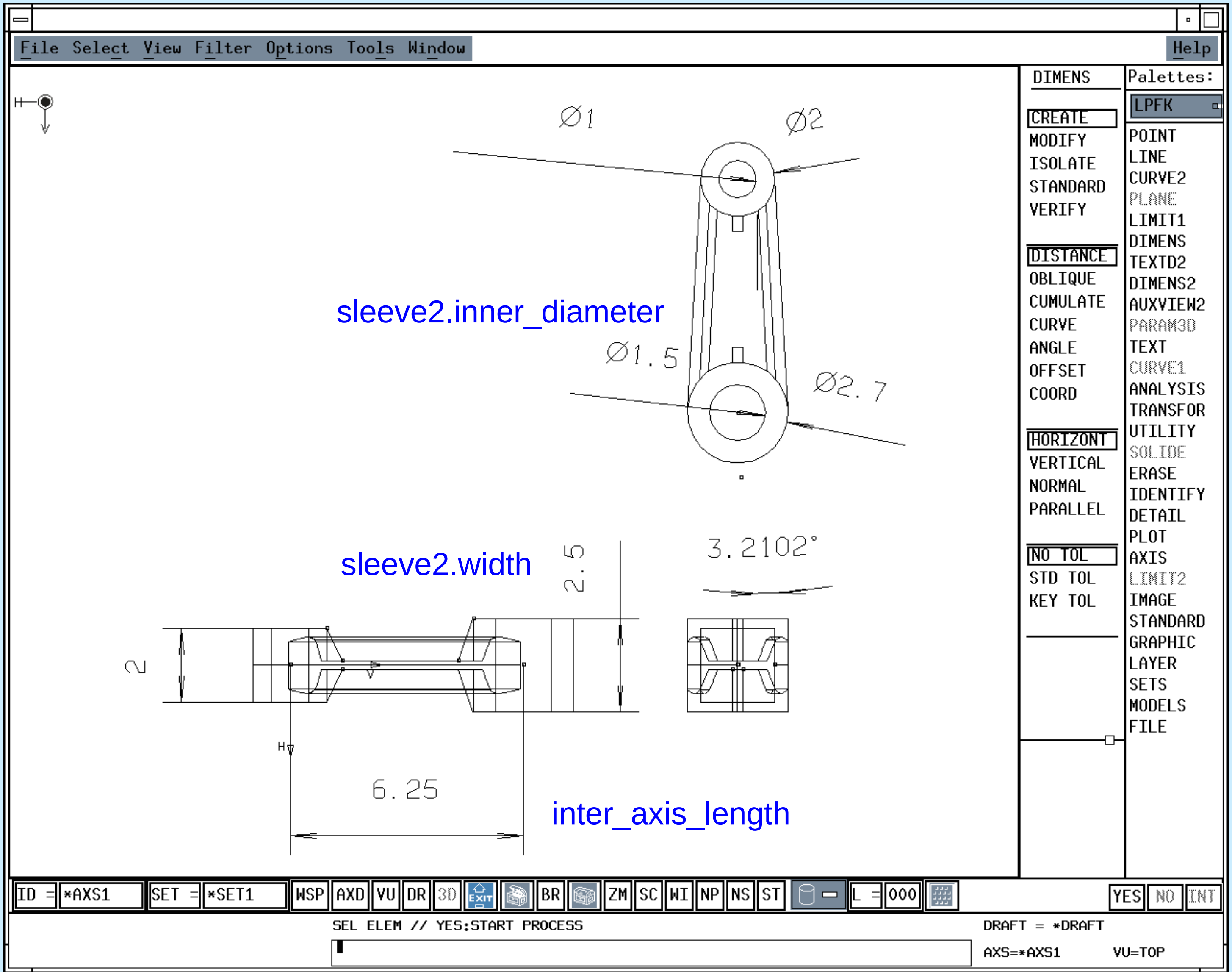
CATIA (CAD tool)

6) response

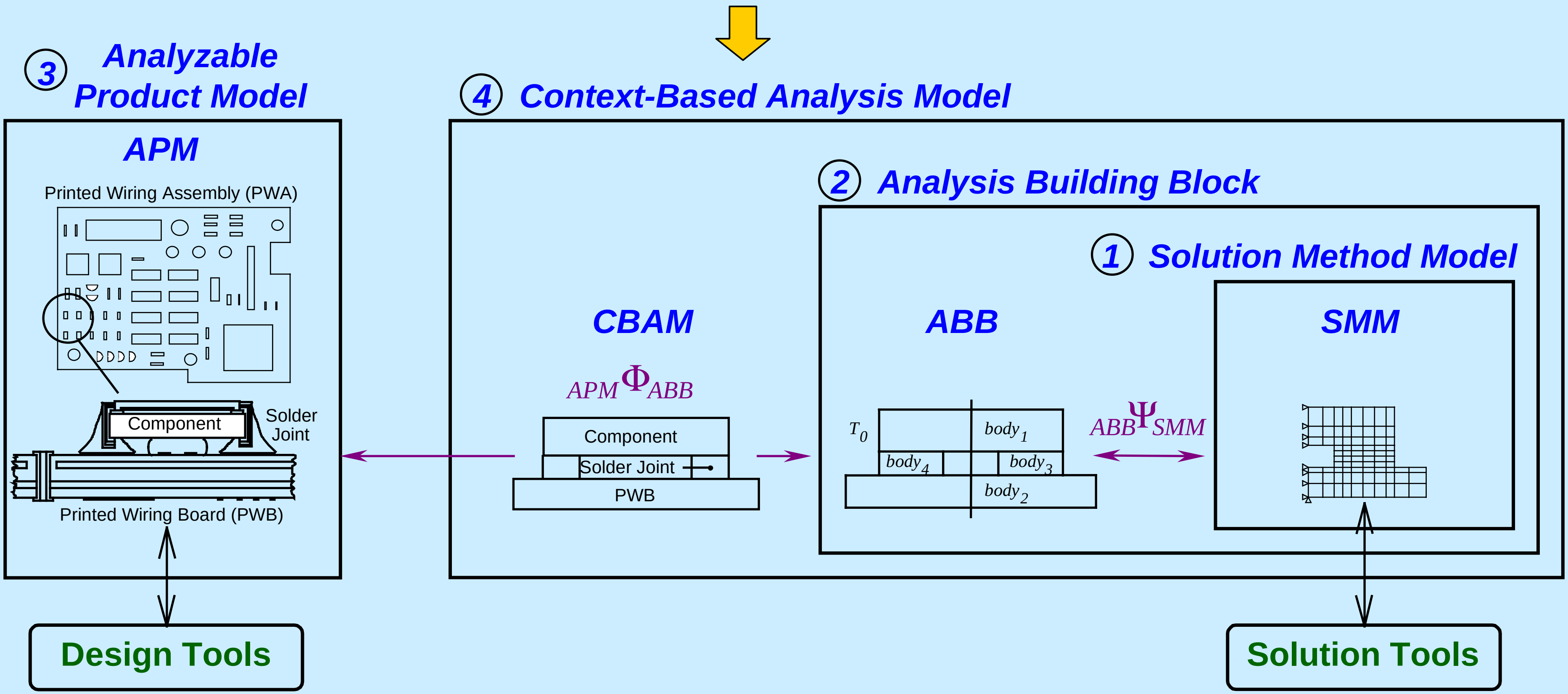
```
part_number : “9162”;
hole1.radius : 2.5;
hole2.radius : 4.0;
length1 : 20.0;
```

0) **Designer**
- Creates design geometry
- Defines APM-compatible parameters/tags

Flap Link Tagging



Multi-Representation Architecture for Design-Analysis Integration



Tutorial Example:
Flap Link Analysis Problems/CBAMs

Flap Link SCN

(2) Torsion Analysis

(1) Extension Analysis
a. 1D Extensional Rod
b. 2D Plane Stress FEA

1. Mode: *Shaft Tension*

2. BC Objects

Flaps down : $F =$ 10000 *lbs*

3. Part Feature *(idealized)*

$L_{eff} =$ 5.0 *in* — 1020 HR Steel

$A =$ 1.13 in^2 — $E=$ 30e6 *psi*

$\sigma_{allowable} =$ 18000 *psi*

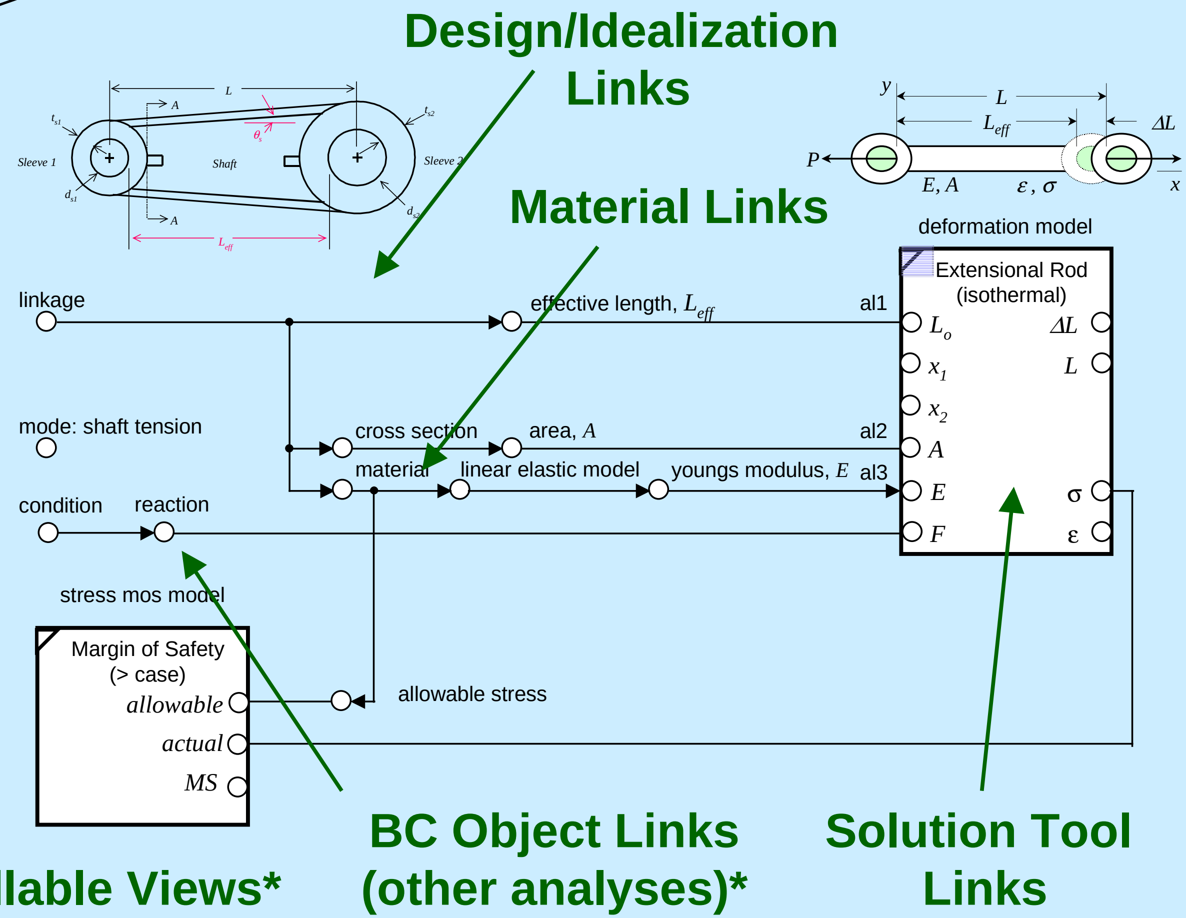
4. Analysis Calculations

$$\sigma = \frac{F}{A} \qquad \Delta L = L_{eff}\frac{\sigma}{E}$$

5. Objective

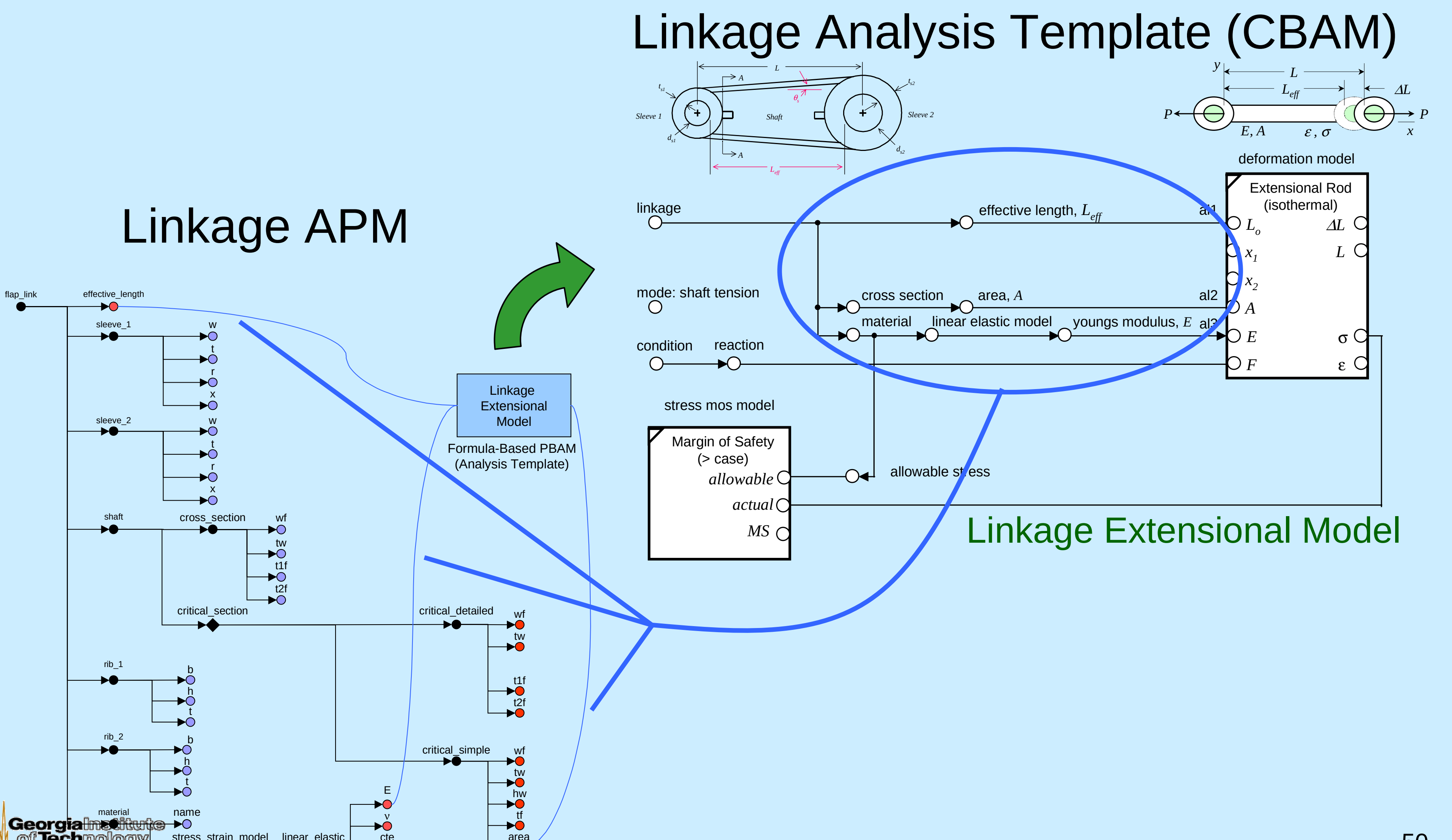
$$MS = \frac{\sigma_{allowable}}{\sigma} - 1 = 1.03$$

(1a) Analysis Problem for 1D Extension Analysis

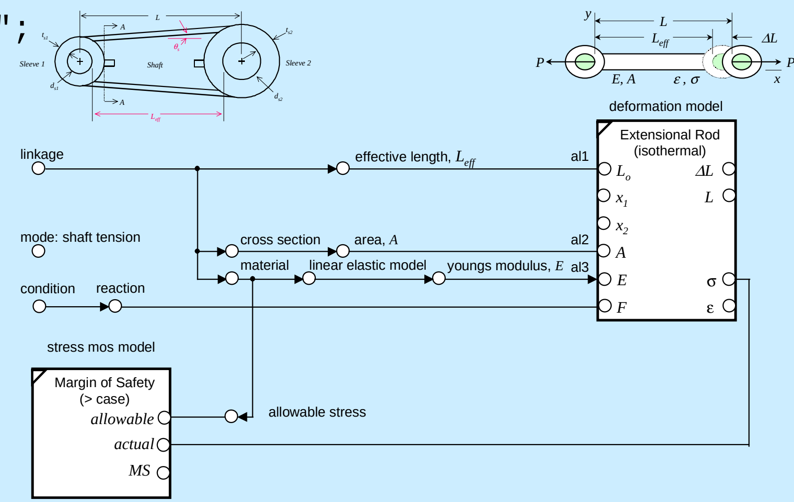


* *Boundary condition objects & pullable views are WIP**

Analysis Template Usage of APM Idealized Attributes



Flap Linkage Extensional Model: Lexical COB Structure



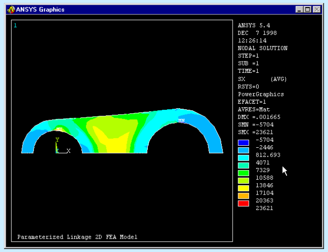

```
COB link_extensional_model SUBTYPE_OF link_analysis_model;
  DESCRIPTION
    "Represents 1D formula-based extensional model.";
  ANALYSIS_CONTEXT
    PART_FEATURE
     link : flap_link
    BOUNDARY_CONDITION_OBJECTS
     associated_condition : condition;
    MODE
     "tension";
    OBJECTIVES
     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;
```

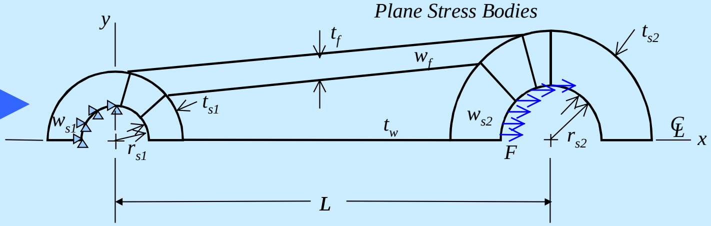
Desired categorization of attributes is shown above (as manually inserted) to support pullable views. Categorization capabilities is a planned XaiTools extension.

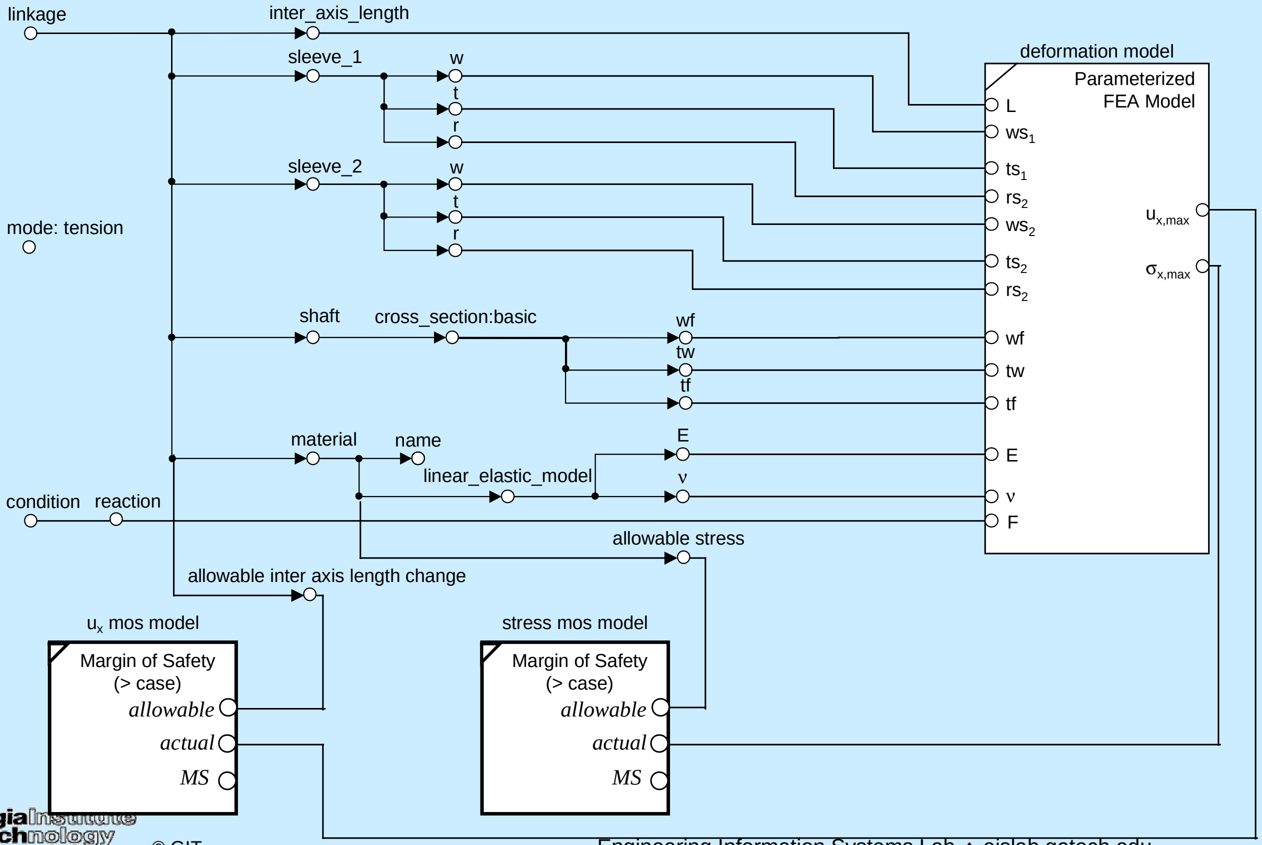
FEA-based Analysis Subsystem

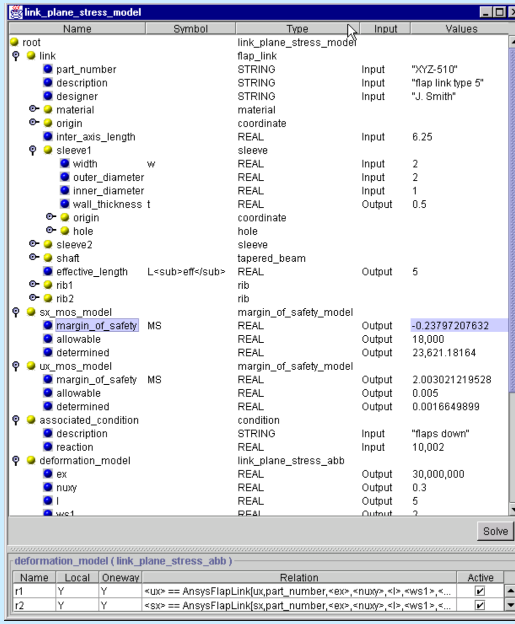
Used in Linkage Plane Stress Model (2D Analysis Problem)

Higher fidelity version
vs. Linkage Extensional Model









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

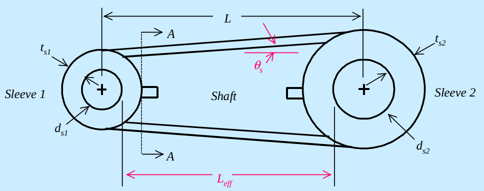
Solve

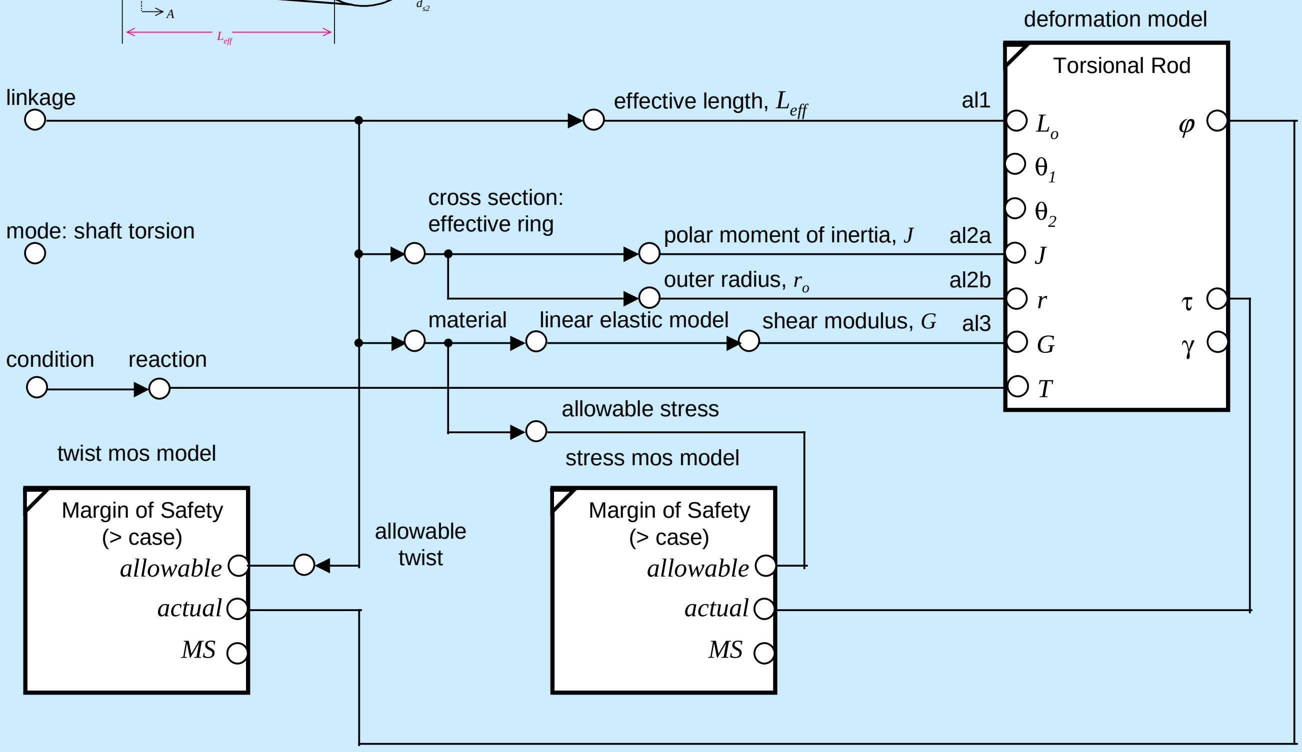
deformation_model (link_plane_stress_abb)

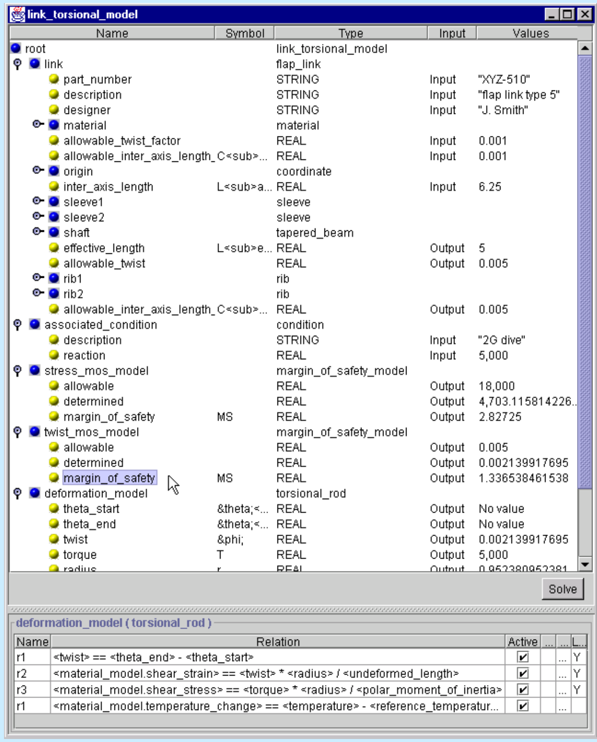
Name	Local	Oneway	Relation	Active
r1	Y	Y	<ux> == AnsysFlapLink[ux,part_number,<ex>,<nuxy>,<l>,<ws1>,<...	✓
r2	Y	Y	<sx> == AnsysFlapLink[sx,part_number,<ex>,<nuxy>,<l>,<ws1>,<...	✓

Flap Linkage Torsional Model

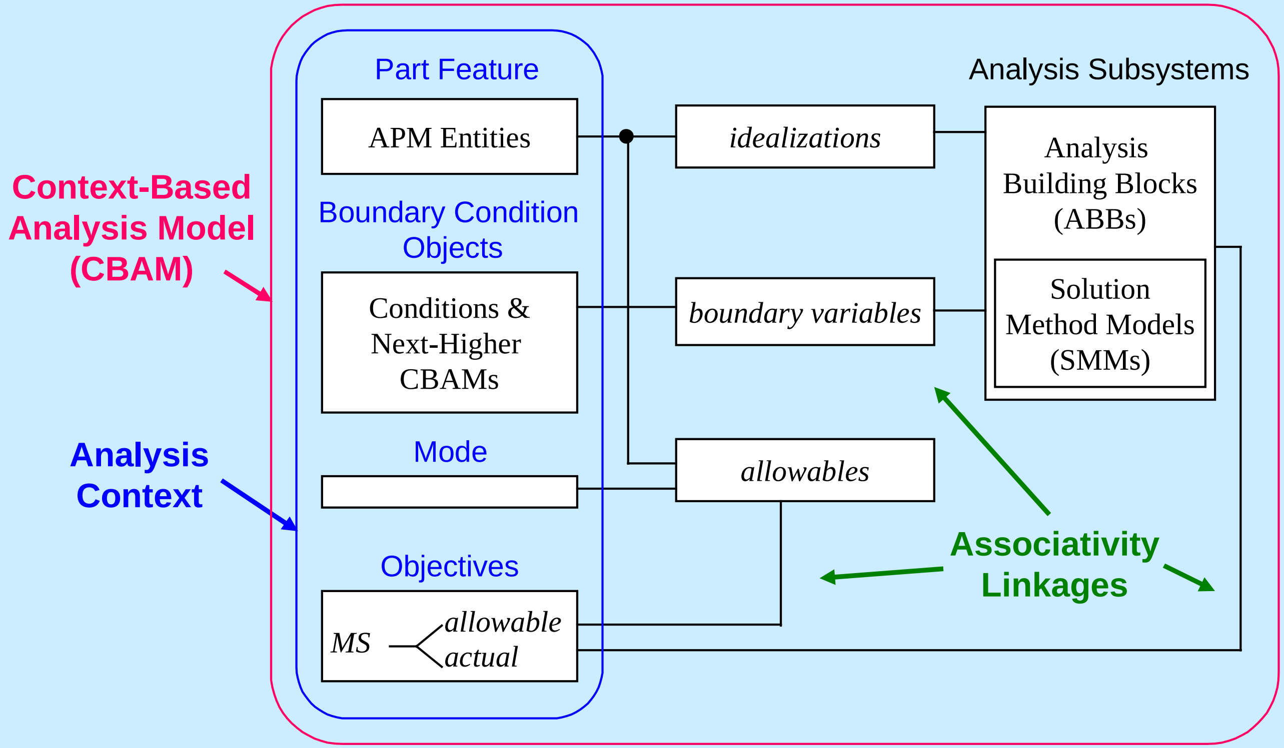
Diverse Mode (Behavior) vs. Linkage Extensional Model







Major Types of Analysis Objects



Analysis Context
- Analysis specification (why vs. how)
- Definable during early planning stages

analysis problem a.k.a: template, context-based analysis model (CBAM), analysis module

CBAM = why + how
= Analysis Context
+ Analysis Subsystems (ABBs, etc.)
+ Associativity Linkages

- Can be new, reused, or adapted template
- Instance can contain one or more runs

Outline

- Analysis Integration Challenges
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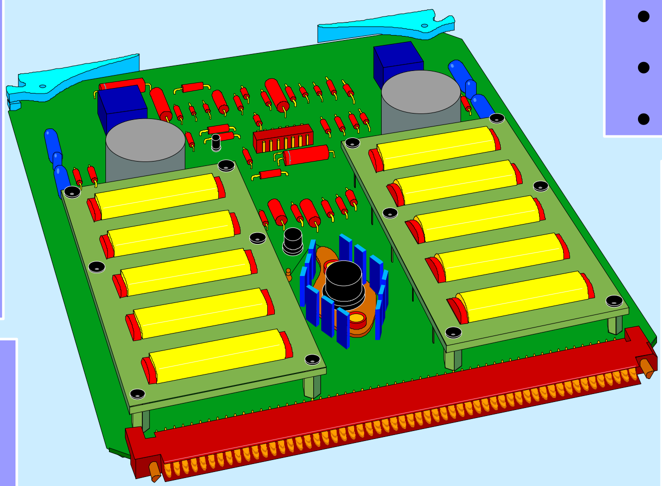
  - Aerospace Structural Analysis
- Summary

STEP AP 210
PWA/B Design Information

Product Structure/ Connectivity
- Functional
- Packaged

Part
- Functionality
- Termination
- Shape 2D, 3D
- Single Level Decomposition
- Material Product
- Characteristics

Physical
- Component Placement
- Bare Board Geometry
- Layout items
- Layers non-planar, conductive & non-conductive
- Material product



Configuration Mgmt
- Identification
- Authority
- Effectivity
- Control
- Requirement Traceability
- Analytical Model
- Document References

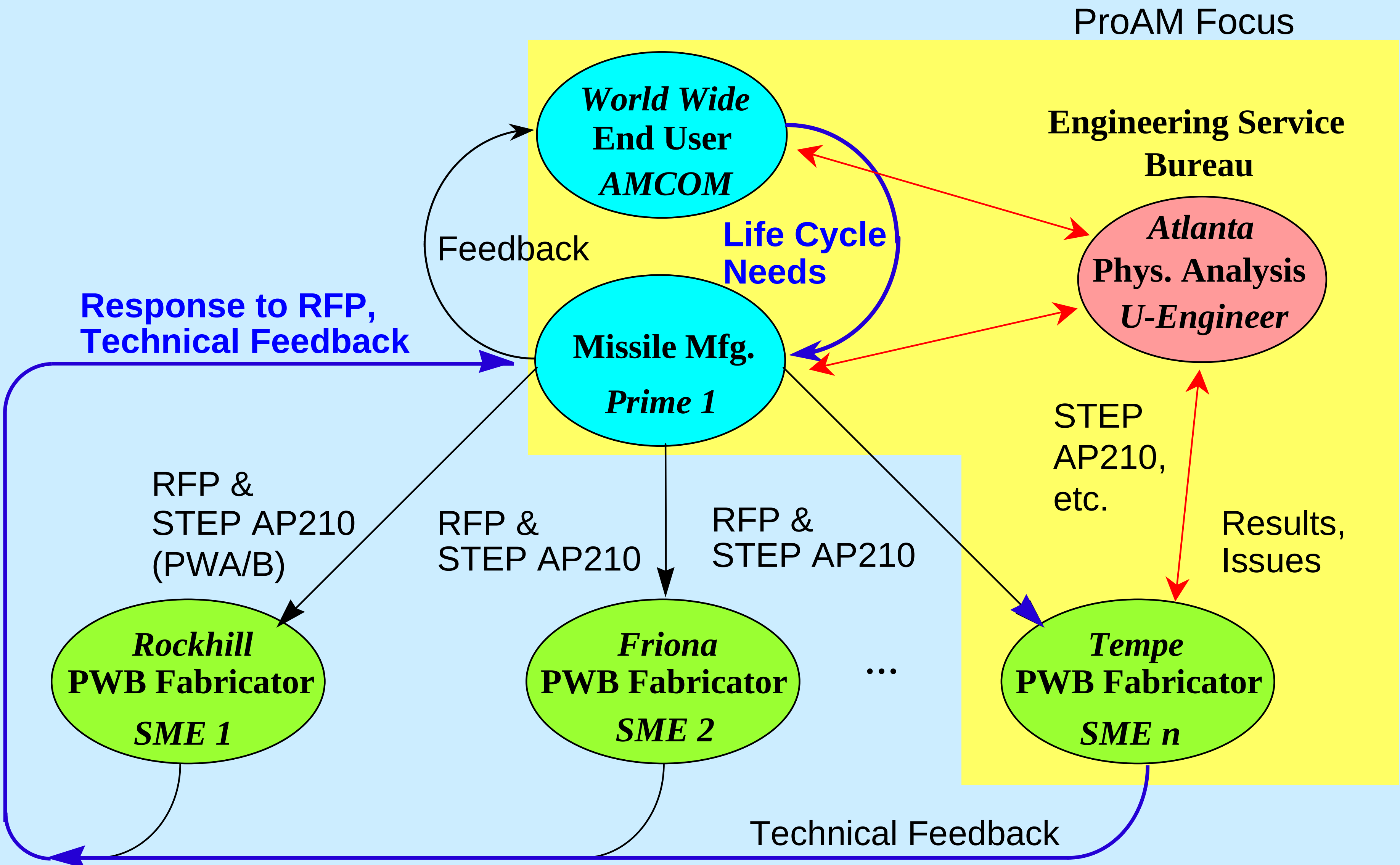
Geometry
- Geometrically Bounded 2-D Shape
- Wireframe with Topology
- Advanced BREP Solids
- Constructive Solid Geometry

Requirements
- Design
- Allocation
- Constraints
- Interface

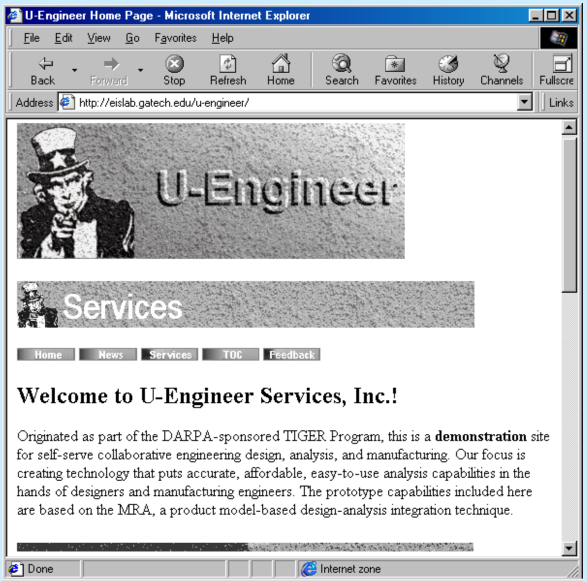
Technology
- Fabrication Design Rules
- Product Design Rules

ProAM Scenario

Highly Automated Internet-based Analysis Modules



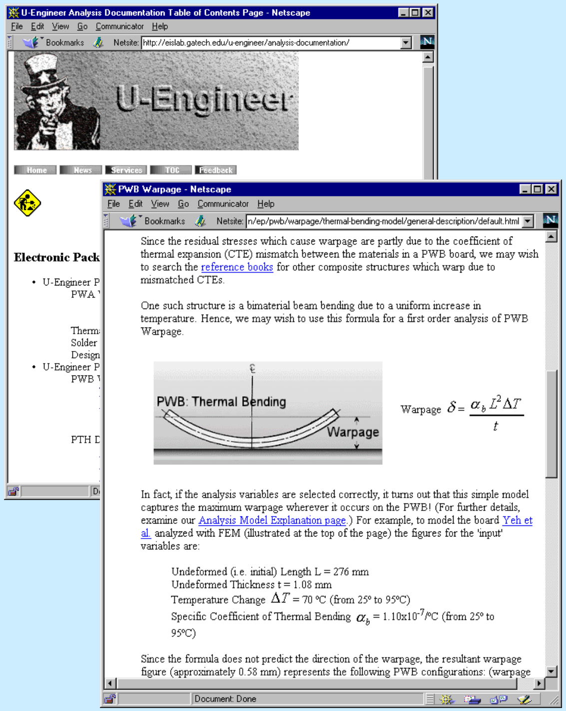
Internet-based Engineering Service Bureaus (ESBs)

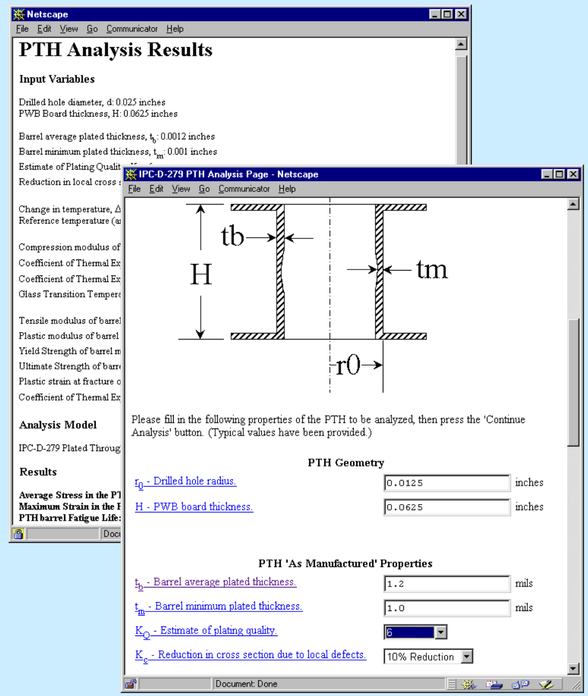


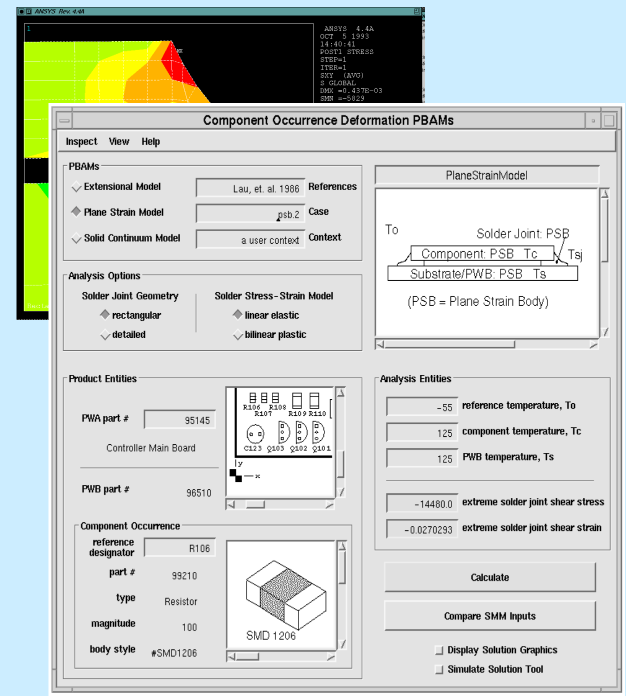
- Self-serve analysis
  - Pre-developed analysis modules in product & process contexts
  - Available via the Internet
  - Standards-driven (STEP, GenCAM ...):
    - » Reduce manual data entry
    - » Highly automated plug-and-play usage
  - Enabled by X-analysis integration technology
- Pay-per-use and/or period
  - Costs averaged across customer base
- Full-serve analysis as needed

u-engineer.com

ProAM Pilot Commercial ESB







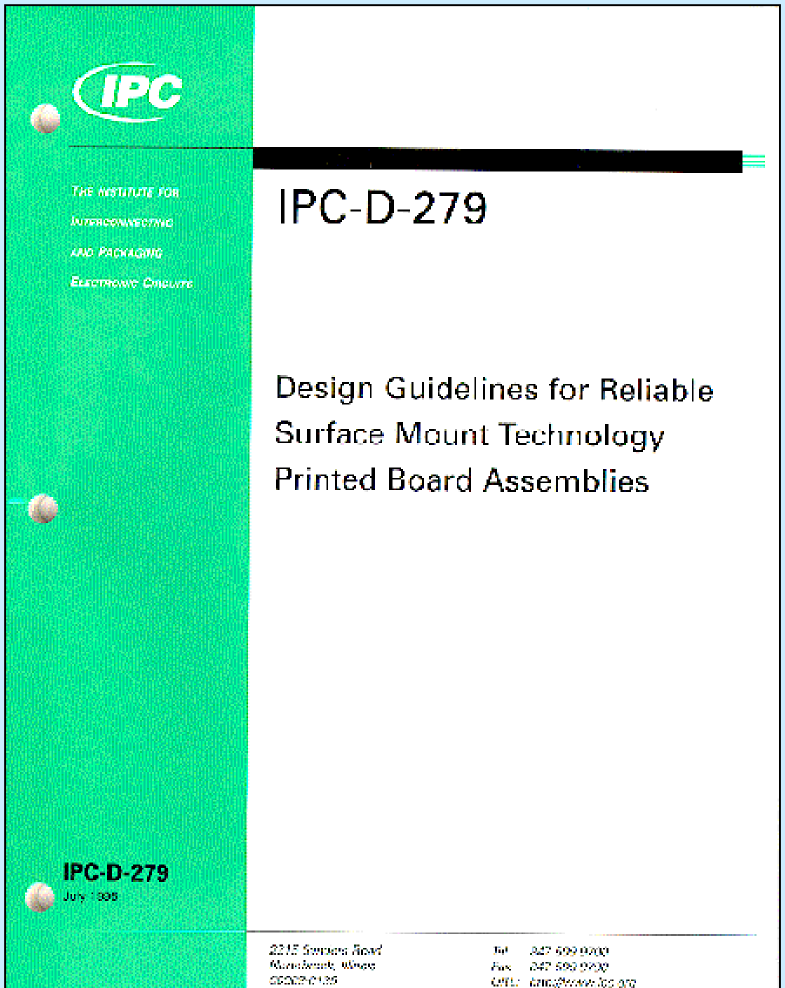
Analysis Documentation

Ready-to-Use Analysis Modules

Lower cost, better quality, fewer delays in supply chain

Note: u-engineer.com is currently hosted at http://eislab.gatech.edu/u-engineer/

IPC-D-279 Plated Through Holes/Vias Analysis Guide



PTH/PTV Fatigue Life Estimation

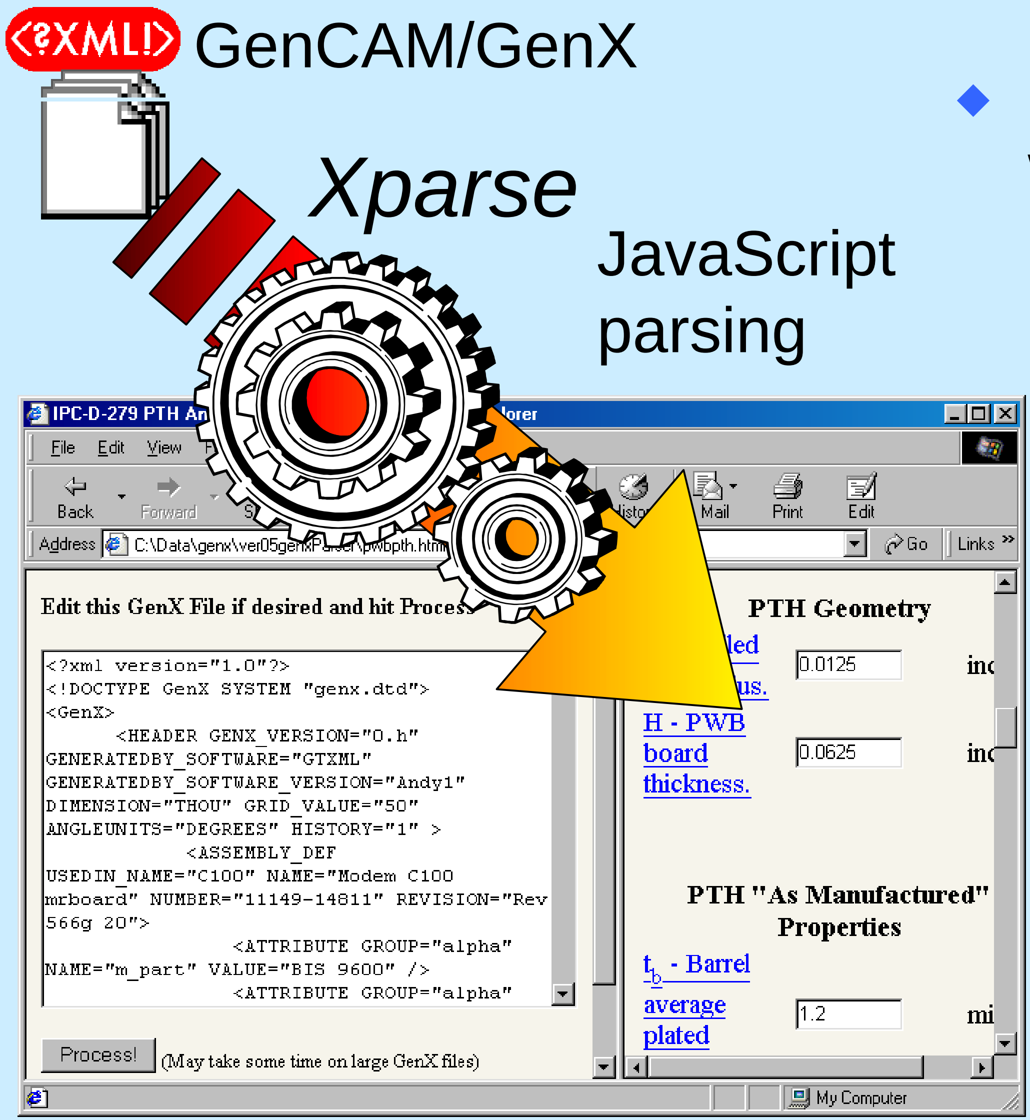
$$\sigma_{avg} = \frac{\left[(\alpha_E - \alpha_{Cu})\Delta T + S_y \cdot \frac{E_{Cu} - E_{Cu}'}{E_{Cu} \cdot E_{Cu}'}\right] A_E \cdot E_E \cdot E_{Cu}'}{A_E \cdot E_E + A_{Cu} \cdot E_{Cu}'}$$

$$\Delta\varepsilon_{avg} = \frac{(\alpha_E - \alpha_{Cu})\Delta T \cdot A_E \cdot E_E - S_y \cdot A_{Cu} \cdot \frac{E_{Cu} - E_{Cu}'}{E_{Cu}}}{A_E \cdot E_E + A_{Cu} \cdot E_{Cu}'}$$

$$N_f^{-0.6} D_f^{0.75} + 0.9 \frac{S_u}{E}\left[\frac{e^{D_f}}{0.36}\right]^{0.1785 \log\frac{10^5}{N_f}} - \Delta\varepsilon = 0$$

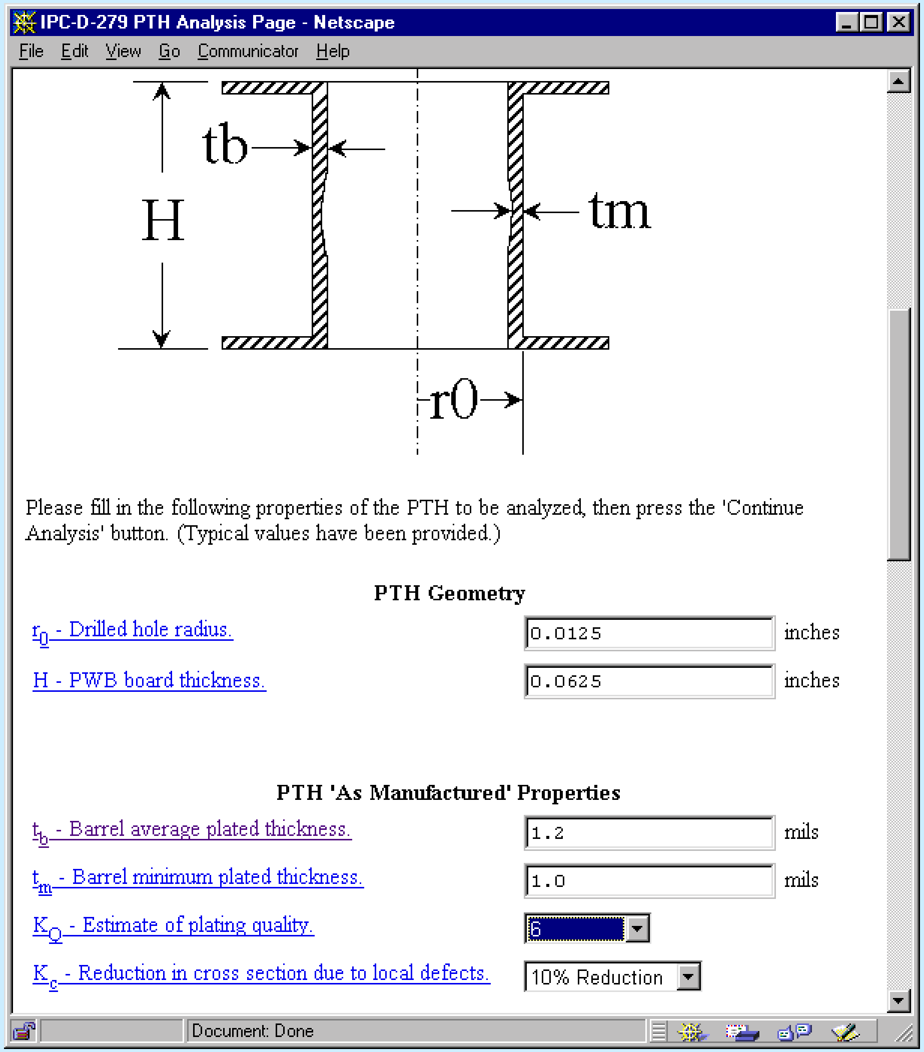
$$N_f(x\%) = N_f(50\%)\left[\frac{\ln(1 - 0.01x)}{\ln(0.5)}\right]^{\frac{1}{\beta}}$$

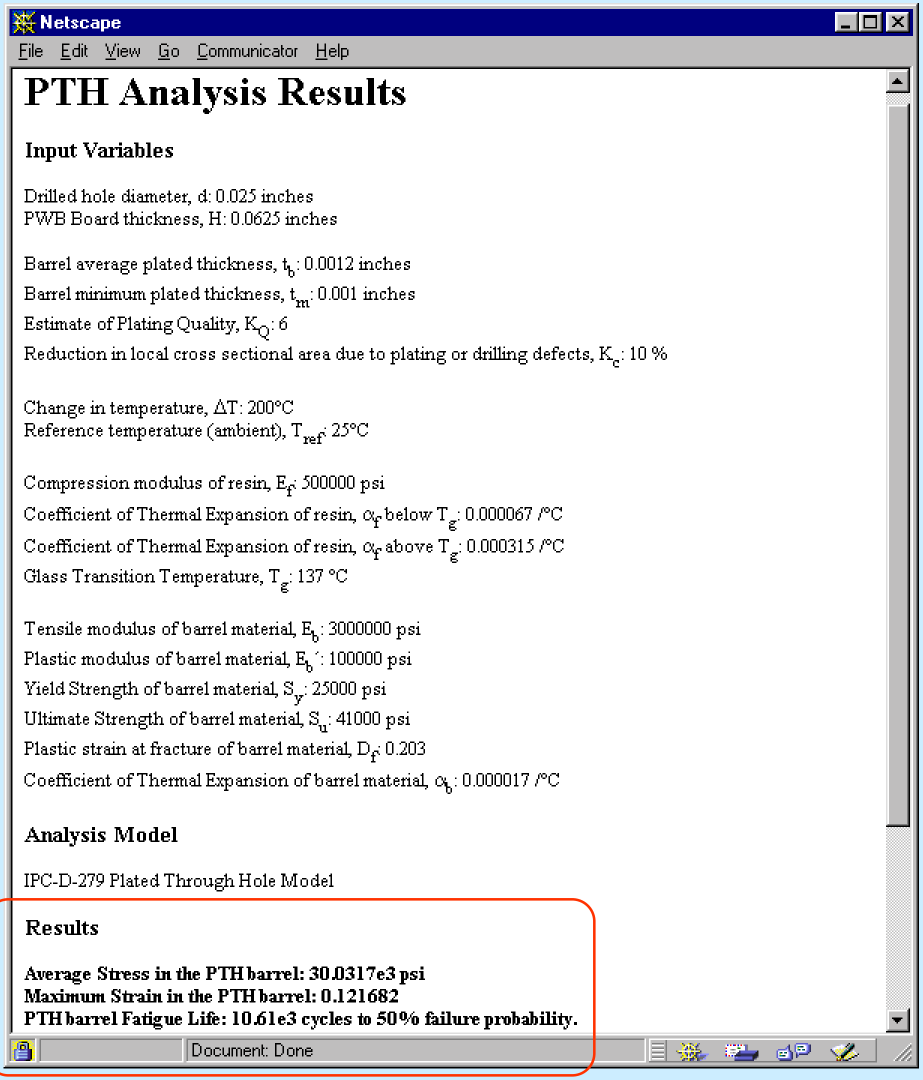
Product Data-Driven IPC-D-279 PTH Analysis Module



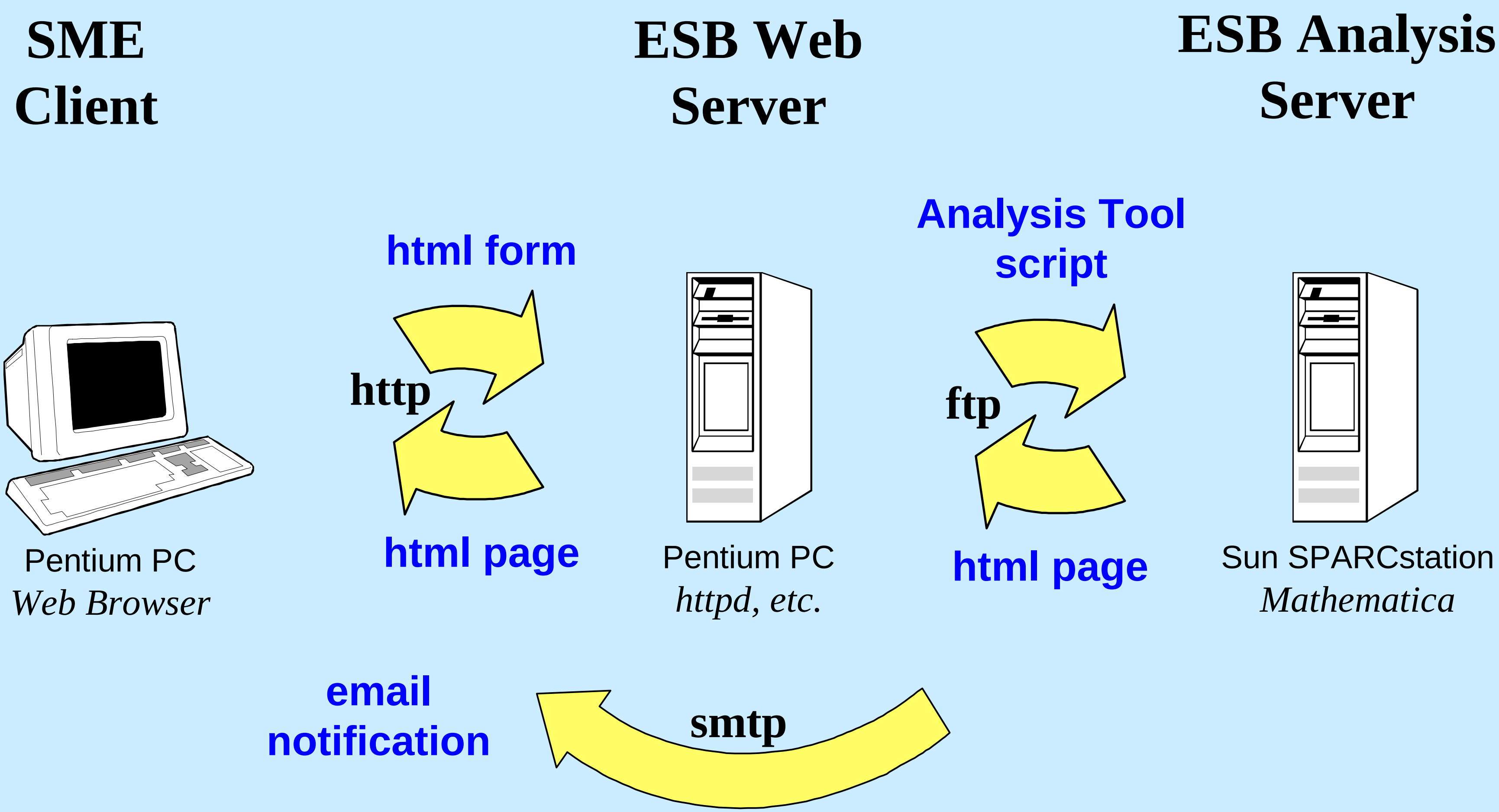
- Data Driven aspect: Web Browser Processes Neutral File
  - \+ Local Browser Computation
  - \+ Less Errors than manual entry
  - \+ Exhaustive search
  - \+ Data Compression (e.g. 100x)
  - \+ Security

Web-based Analysis Results





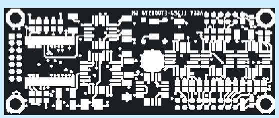
Analysis Data Flow
Web-based Approach



ProAM Design-Analysis Integration

Electronic Packaging Examples: PWA/B

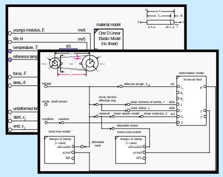
ECAD Tools
*Mentor Graphics, Accel**



Modular, Reusable Template Libraries

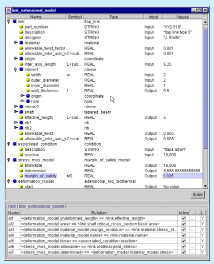
Analysis Modules (CBAMs) of Diverse Mode & *Fidelity*

Analysis Tools



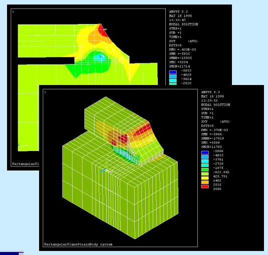
STEP AP210, GenCAM**, PDIF*

XaiTools

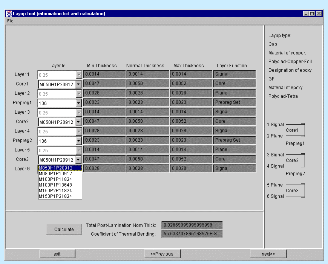


General Math *Mathematica*

FEA *Ansys*



PWB Layup Tool

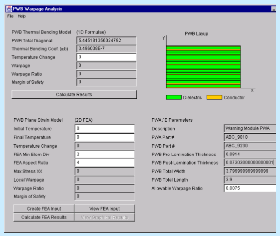


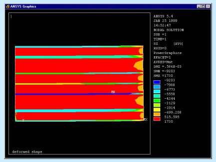
Analyzable Product Model

XaiTools

Solder Joint Deformation — ***1D, 2D, 3D***

PWB Warpage — ***1D, 2D***

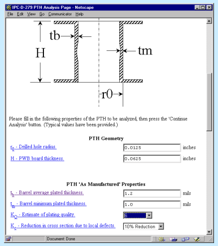


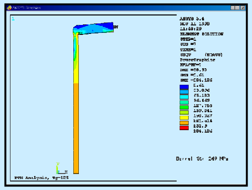


Laminates DB

Materials DB

PTH Deformation & Fatigue** — ***1D, 2D***

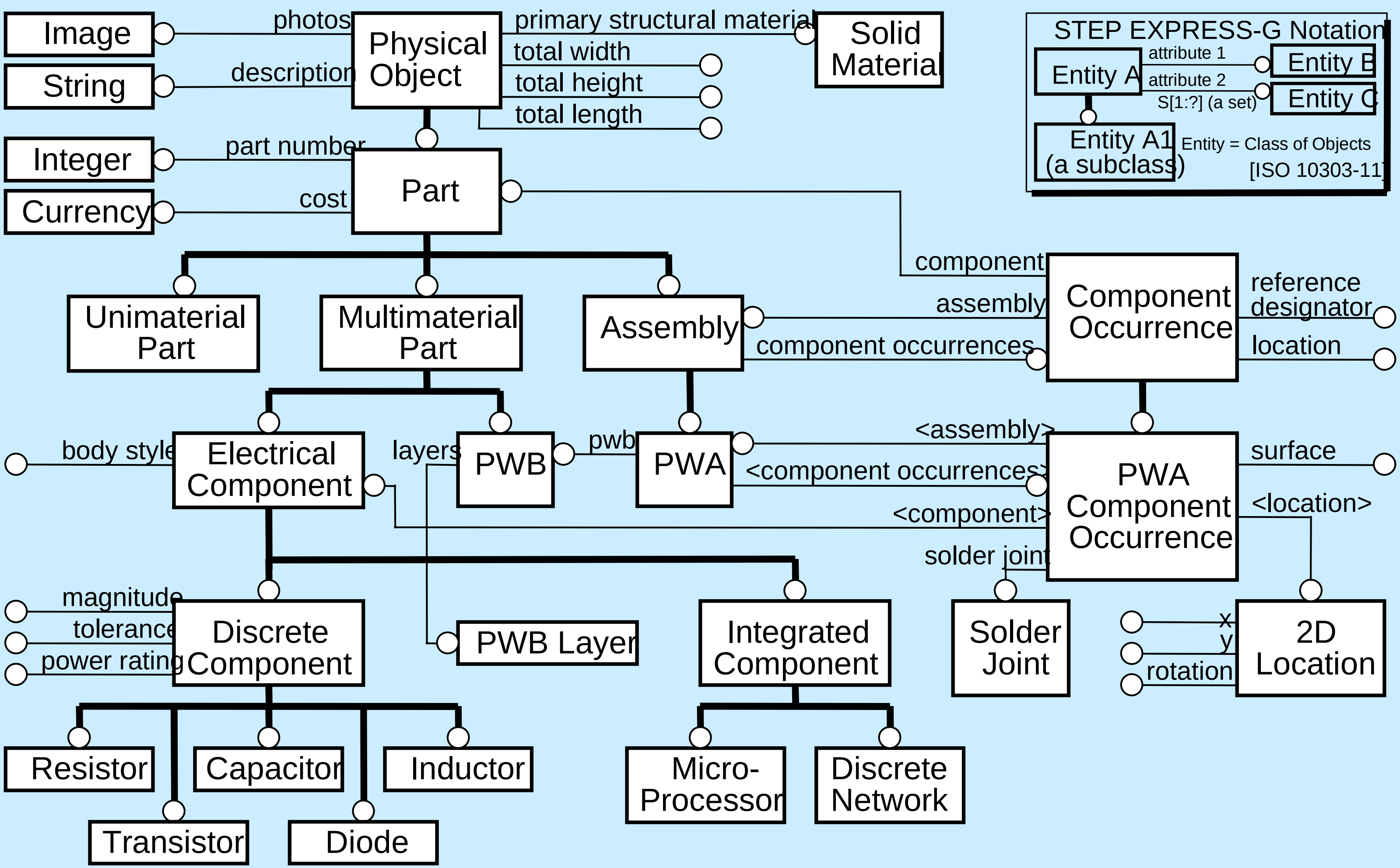




* = Item not available in *XaiTools* prototype (all others have working examples)
** = Item available via U-Engineer.com, but not in *XaiTools* prototype

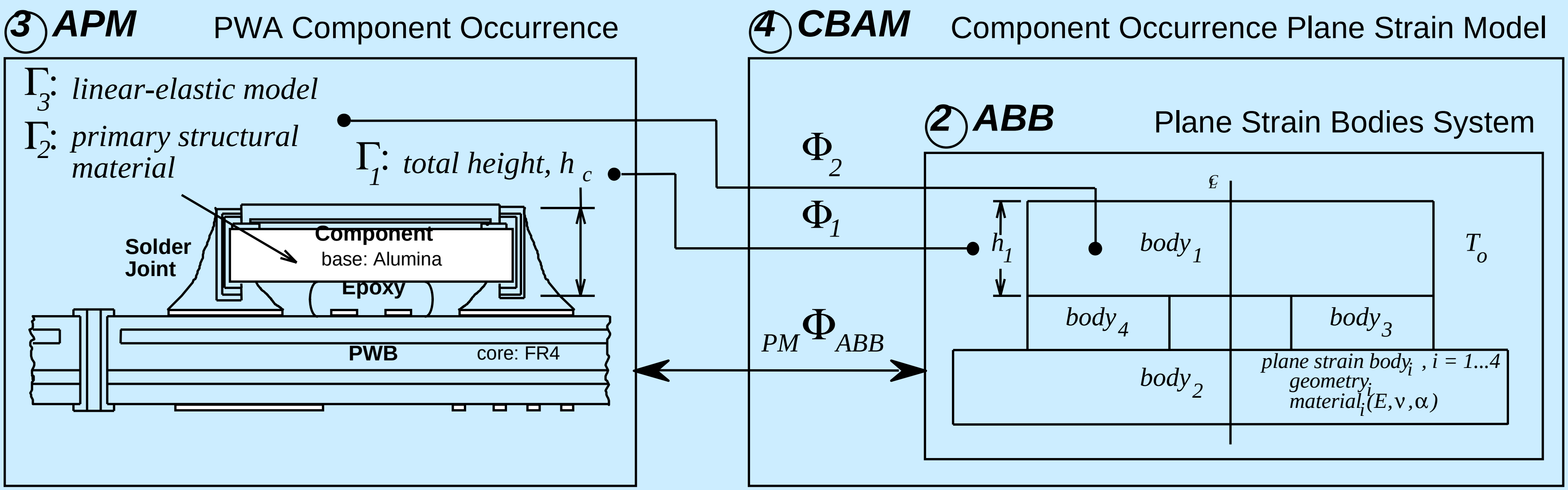
PWA/B Analyzable Product Model

(partial)



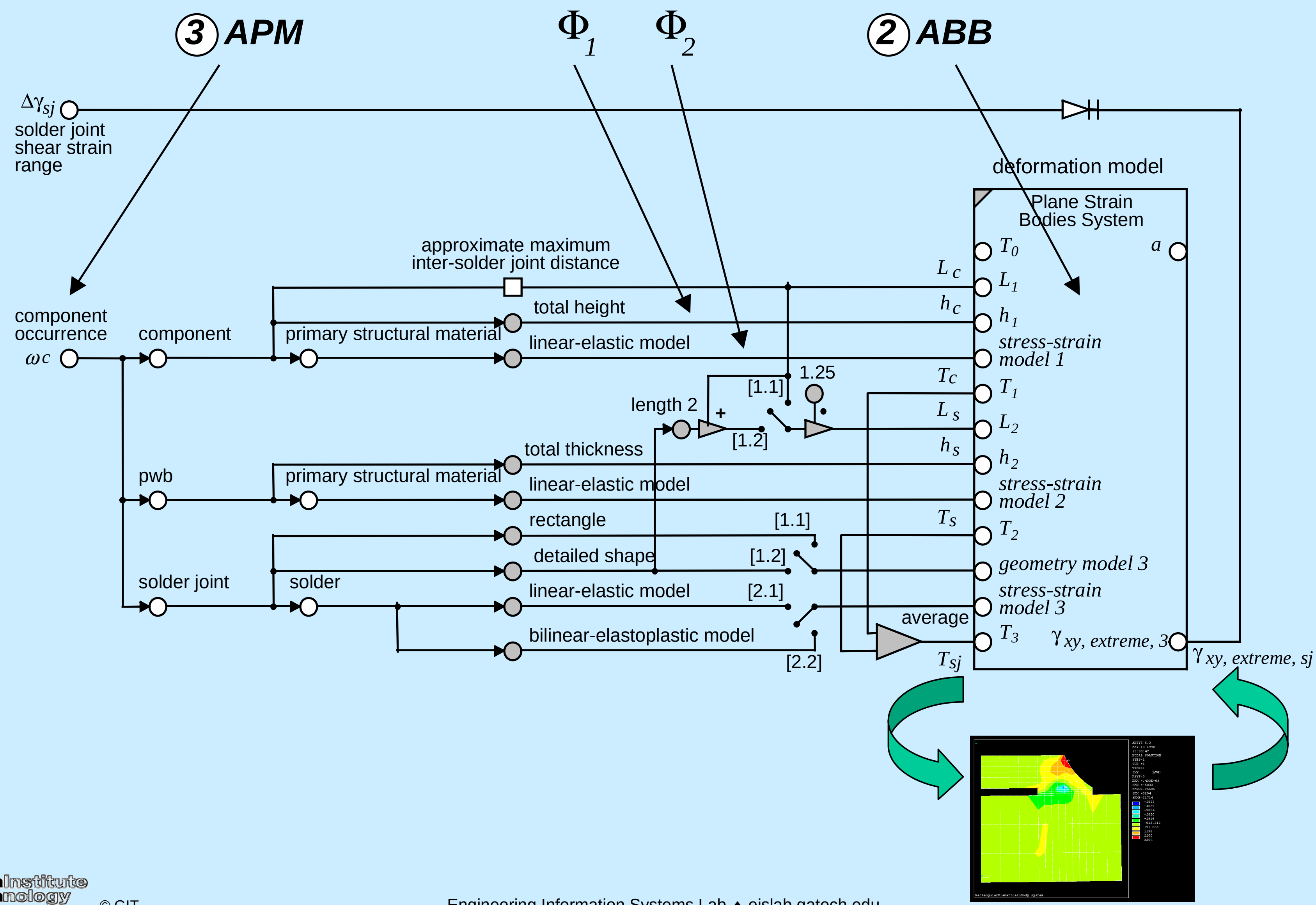
Solder Joint Deformation CBAM

Informal Associativity Mapping



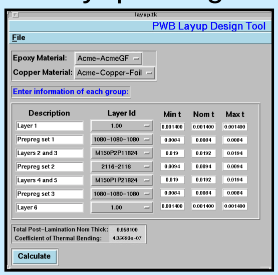
Solder Joint Deformation CBAM

Constraint Schematic



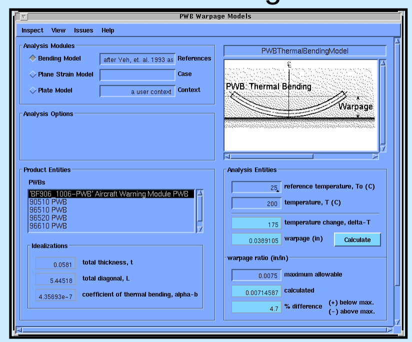
Iterative Design & Analysis
with Multifidelity PWB Warpage Modules (CBAMs)

PWB Layup Design Tool



Layup Redesign

Thermal Bending Model



Quick Formula-based Check

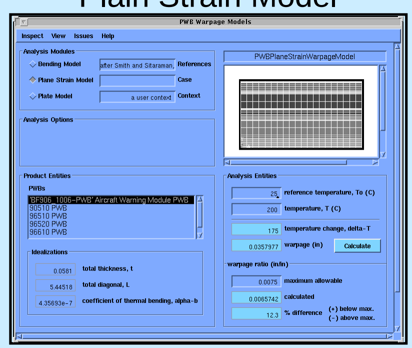
$$\delta = \frac{\alpha_b L^2 \Delta T}{t}$$

$$\alpha_b = \frac{\sum w_i \alpha_i y_i}{t/2 \sum w_i}$$

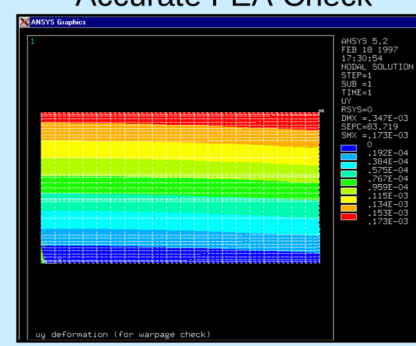
Analyzable Product Database

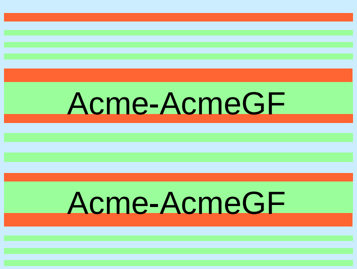
PWB Warpage Modules

Plain Strain Model



Accurate FEA Check



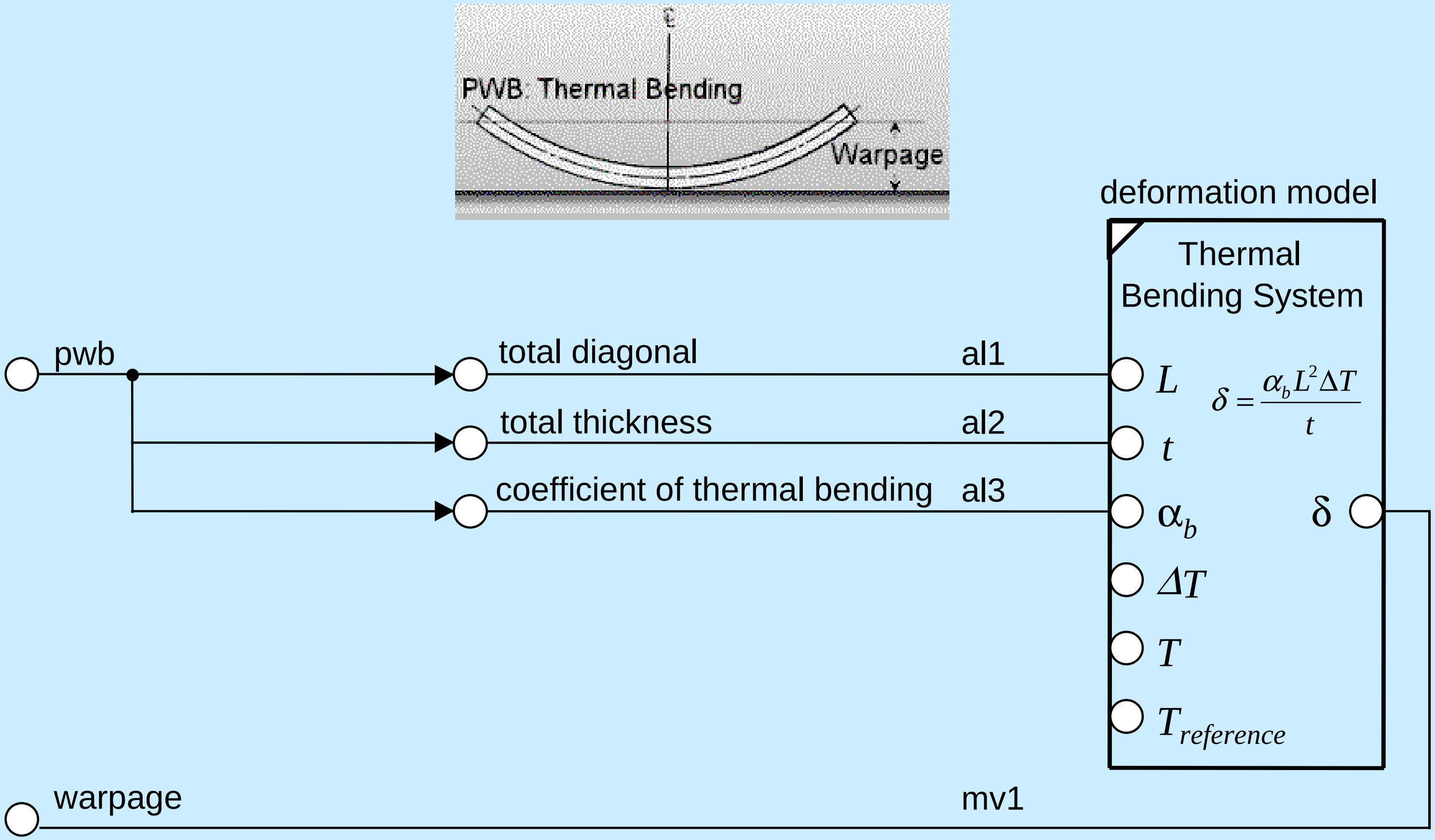


3 x 1080
2 x 2116
3 x 1080

1 Oz. Cu
2 Oz. Cu
1 Oz. Cu
1 Oz. Cu
2 Oz. Cu
1 Oz. Cu

PWB Warpage CBAM

PWB Thermal Bending Model (1D formula-based)



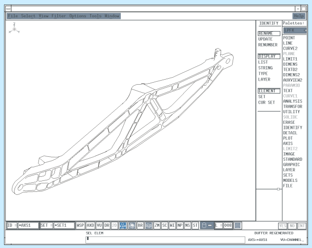
Flexible High Diversity Design-Analysis Integration

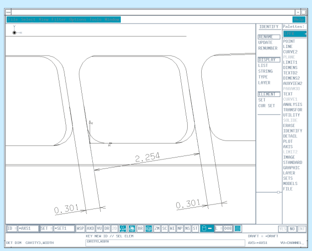
Aerospace Examples:

"Bike Frame" / Flap Support Inboard Beam

MCAD Tools

CATIA



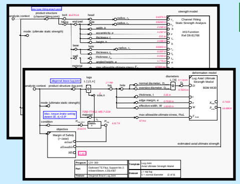


Materials DB

MATDB-like

Fasteners DB

FASTDB-like



Modular, Reusable Template Libraries

Analyzable Product Model

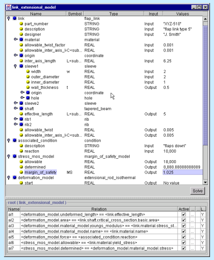
XaiTools

Analysis Modules (CBAMs) of Diverse Feature:Mode, & *Fidelity*

XaiTools

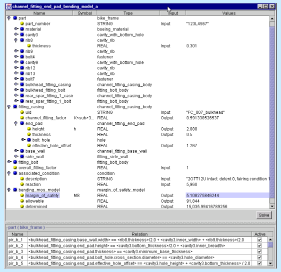
1.5D

Lug: Axial/Oblique; Ultimate/Shear



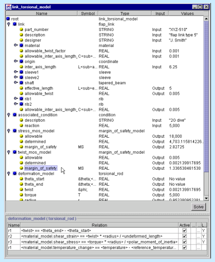
1.5D

Fitting: Bending/Shear



3D

Assembly: Ultimate/ FailSafe/Fatigue*



Analysis Tools

In-House

*Tool Template**

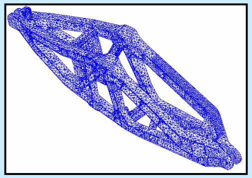
or

General Math

Mathematica

FEA

*Elfini**



* = Item not available in working prototype yet (all others have working examples)

Today's Fitting Catalog Documentation

from DM 6-81766 Design Manual

Calculation Steps

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.

Channel Fitting End Pad Bending Analysis

1. End Pad Analysis – Bending

<u>Step 1</u>: Compute $\frac{r_1}{h}$ and $\frac{b}{h}$.

<u>Step 2</u>: 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.

<u>Step 3</u>: Determine the bending stress, f_{be}:

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

<u>Step 4</u>: 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}.

<u>Step 5</u>: The margin of safety is

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

2. End Pad Analysis – Shear

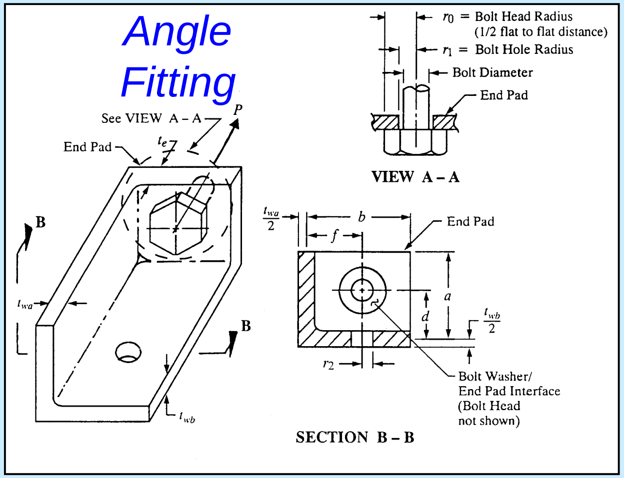
<u>Step 1</u>: Actual shear stress is

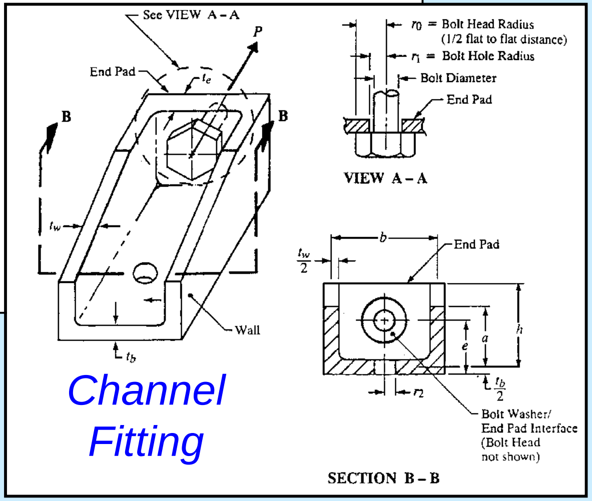
$$f_{se} = \frac{P}{2\pi \, r_0 \, t_e}$$

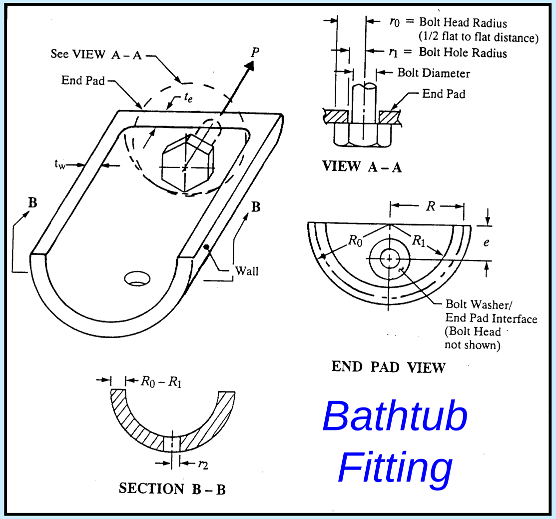
<u>Step 2</u>: The margin of safety is

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

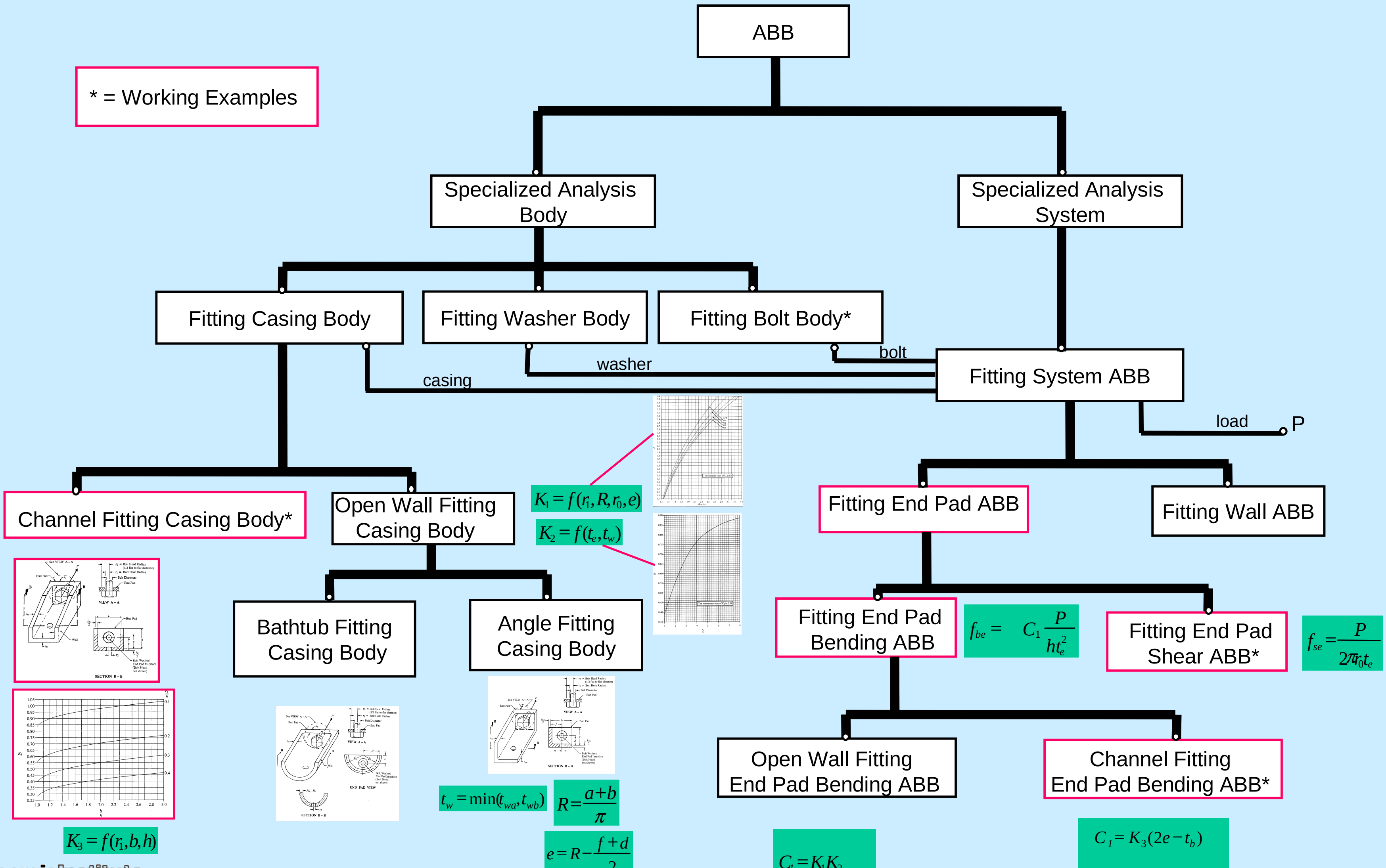
Categories of Idealized Fittings



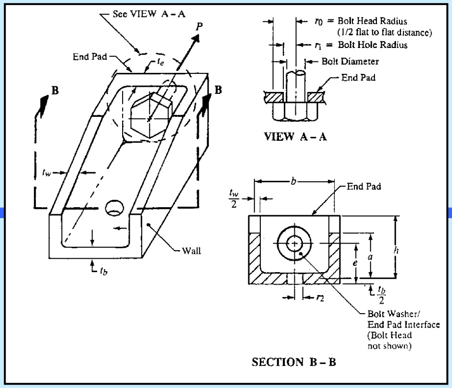




Object-Oriented Hierarchy of Fitting ABBs

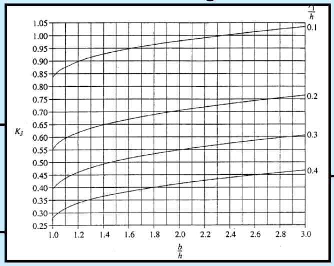


Channel Fitting System ABBs



End Pad Bending Analysis

DM 6-81766 Figure 3.3



r3

- bolt.hole.radius, r_1
- end_pad.height, **h**
- end_pad.width, **b**

r1: $\frac{r_1}{h}$

r2: $\frac{b}{h}$

channel fitting factor, K_3

- end_pad.eccentricity, **e**
- base.thickness, t_b
- end_pad.thickness, t_e
- load, P

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

actual bending stress, f_{be}

End Pad Shear Analysis

r1

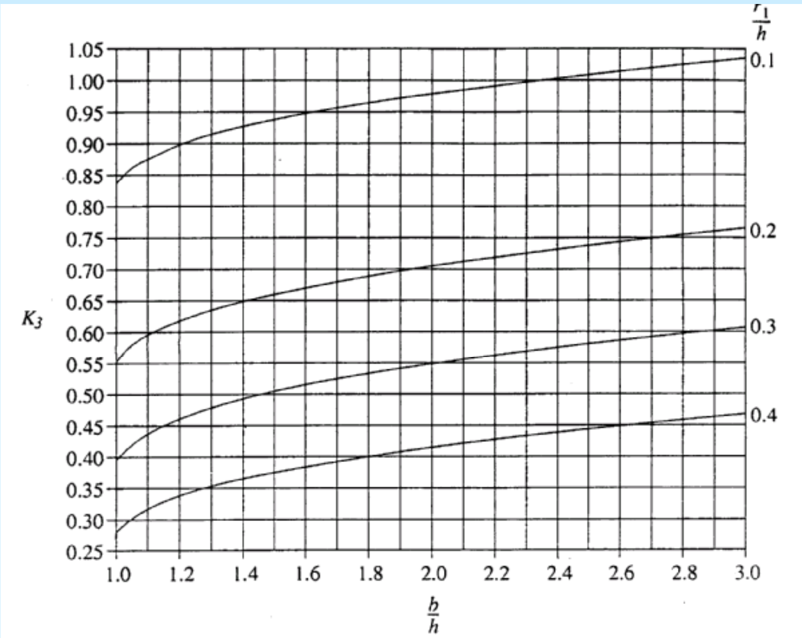
- bolt.head.radius, r_0
- end_pad.thickness, t_e
- load, P

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

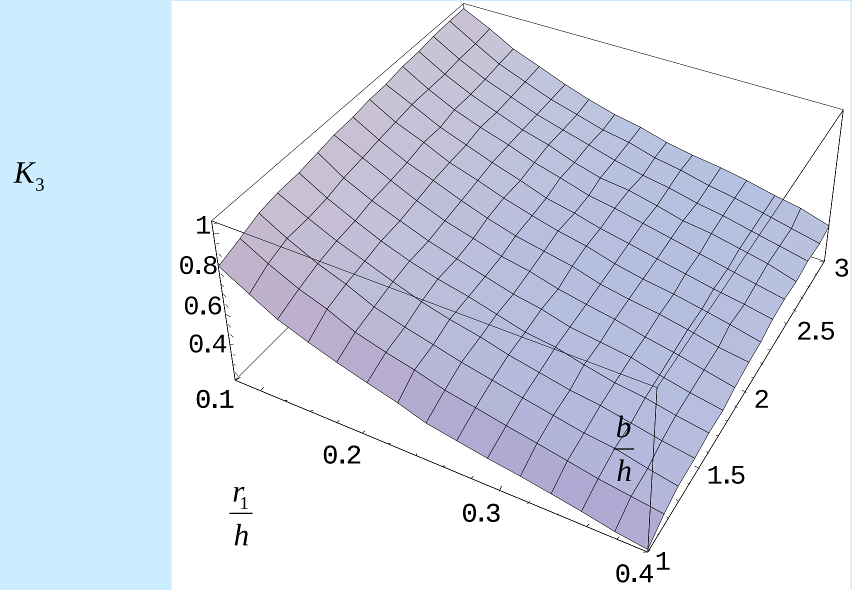
actual shear stress, f_{se}

Implementation of Channel Fitting Factor, K3 as a Reusable Relation in an External Tool

Design Manual Curves

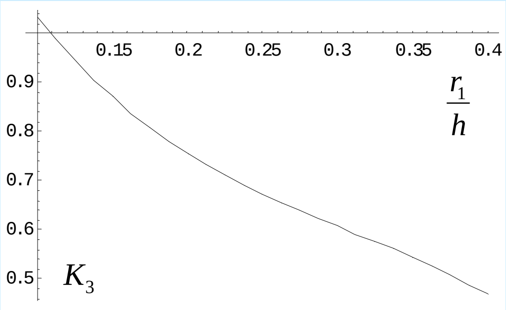


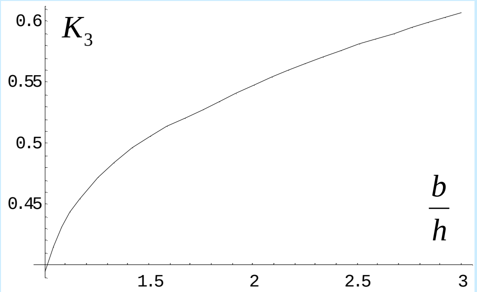
Mathematica Implementation



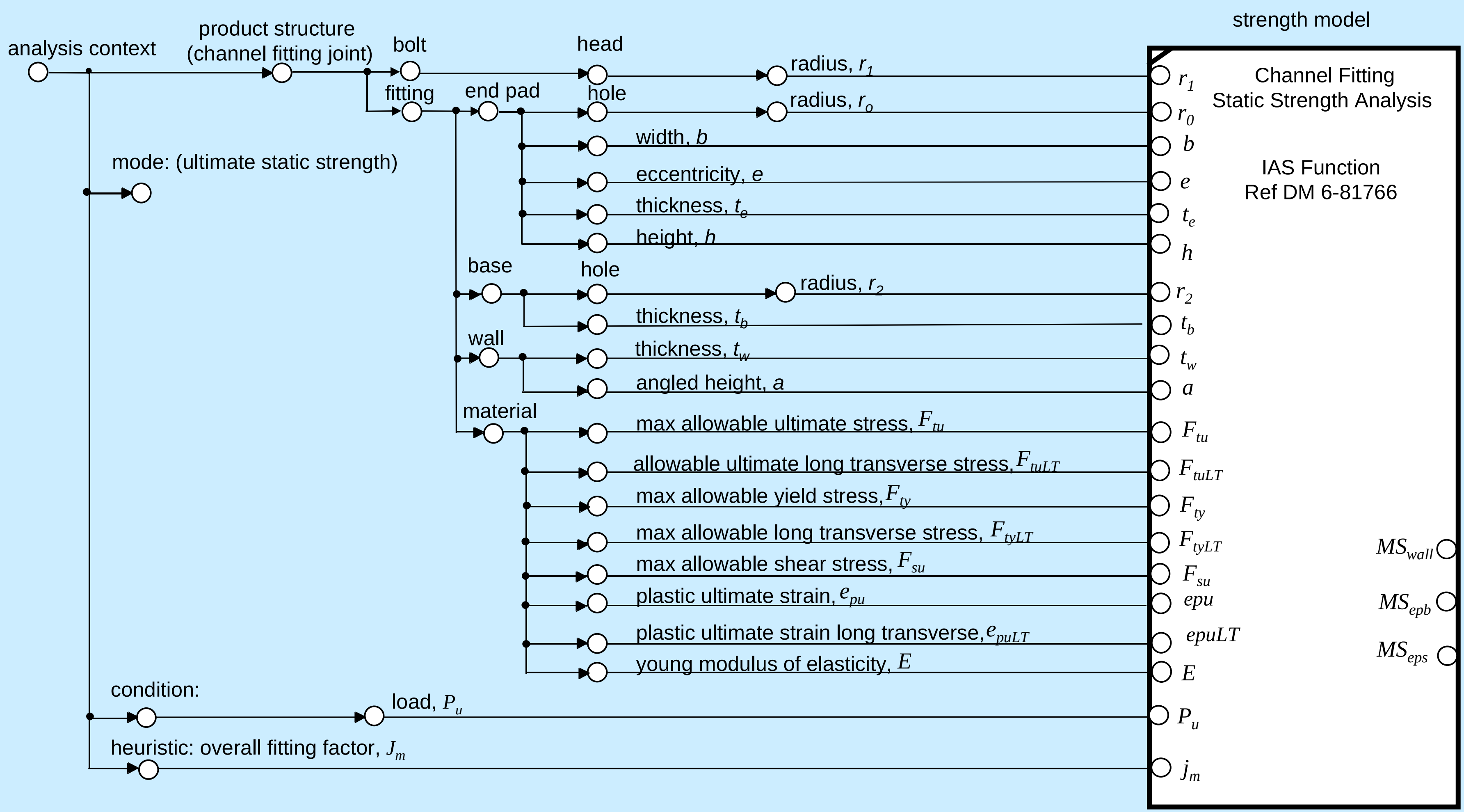
r_1/h = 0.1		r_1/h = 0.2		r_1/h = 0.3		r_1/h = 0.4	
b/h	K_3	b/h	K_3	b/h	K_3	b/h	K_3
1.0	0.836	1.0	0.5525	1.0	0.395	1.0	0.28
1.04	0.8575	1.04	0.575	1.04	0.415	1.04	0.2975
1.1	0.8752	1.1	0.596	1.1	0.437	1.1	0.317
1.2	0.898	1.2	0.618	1.2	0.461	1.18	0.335
1.34	0.92	1.34	0.641	1.34	0.485	1.34	0.359
1.5	0.938	1.5	0.66	1.5	0.505	1.5	0.375
1.8	0.9645	2.0	0.705	2.02	0.55	2.0	0.415
2.1	0.985	2.54	0.74	2.4	0.575	2.52	0.445
3.0	1.035	3.0	0.756	3.0	0.607	3.0	0.468

DM 6-81766 Graph (Figure 3.3)





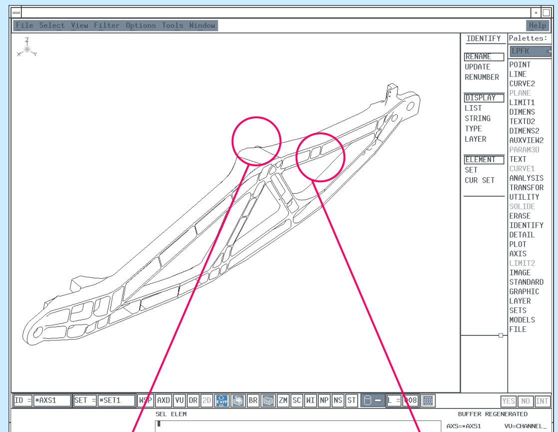
Reusable Channel Fitting Analysis Module (CBAM)



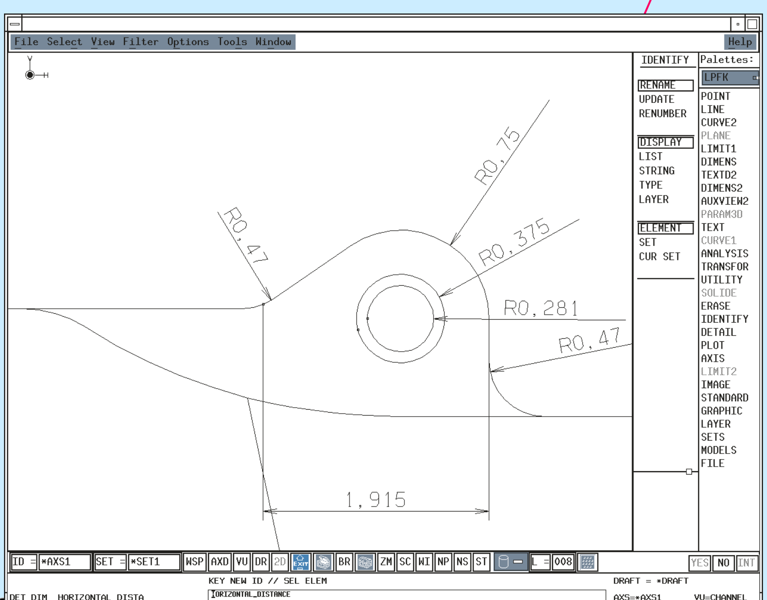
Application to an Aerospace Part

APM Associativity with Tagged CATIA Model

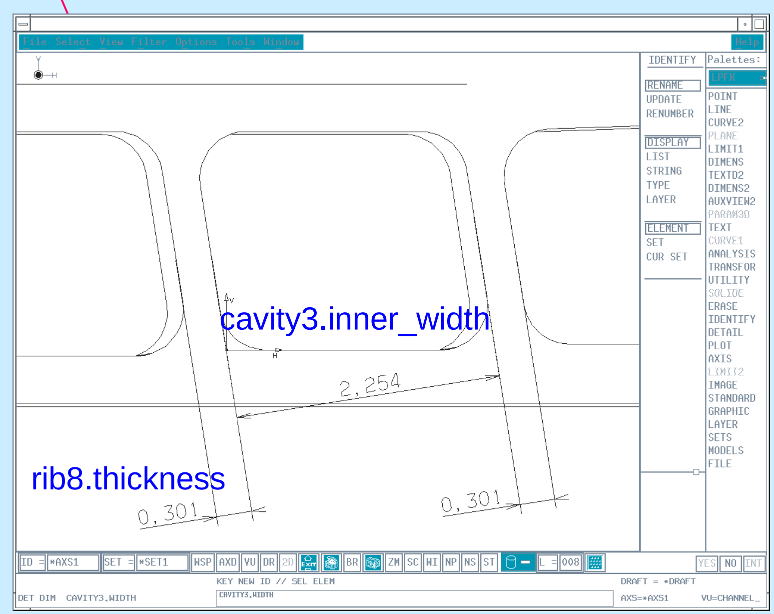
Bike Frame
CATIA CAD Model



Diagonal Brace Lug



Bulkhead Fitting Casing

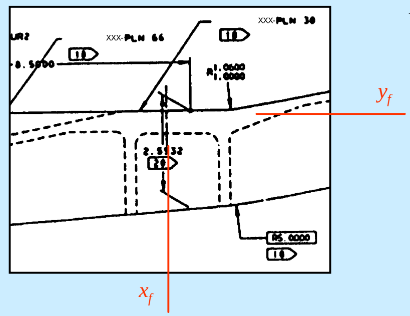


Explicit Capture of Idealizations

(part-specific template adaptation in bike frame case)

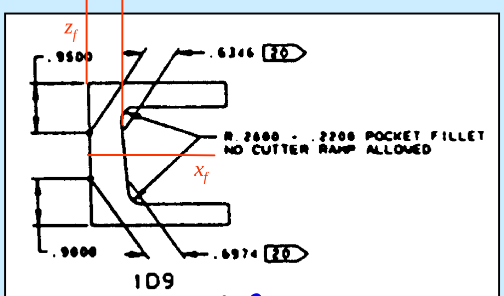
Idealized Features

Features/Parameters Tagged in CAD Model (CATIA)

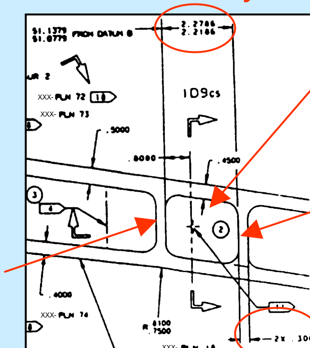


Γ_2

cavity3.base.minimum_thickness



cavity3.width, w_3



cavity 3

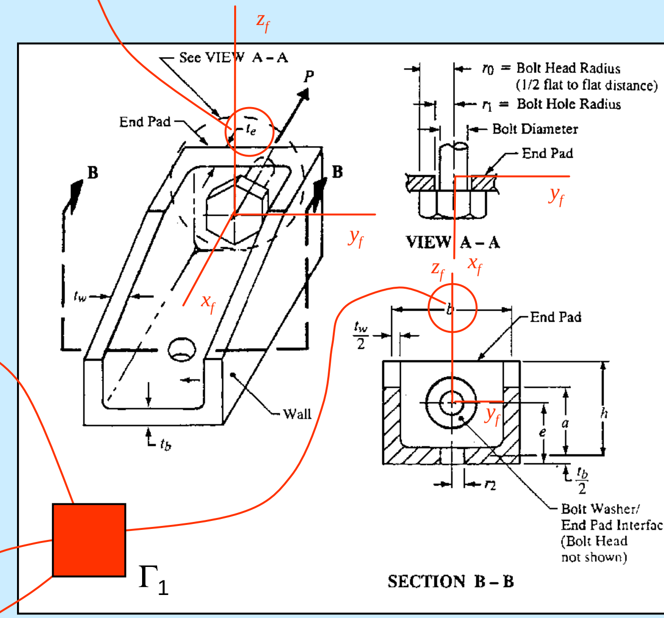
rib9

rib8

$= t_8, t_9$

rib8.thickness

rib9.thickness



Γ_1

Tension Fitting Analysis

Missing in Today's Process

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

Today's Typical Fitting Analysis

Idealized CAD data manually transformed and input

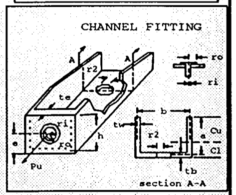
Missing Design-Analysis Associativity

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"

TENSION FITTING TYPE

CHANNEL FITTING



Material Properties & Geometry:

Ftu =	67000	PSI	Pu =	5960	LBS
FtuLT =	65000	PSI	E =	10000000	PSI
Fty =	57000	PSI	ro =	0.5240	IN
FtyLT =	52000	PSI	ri =	0.4375	IN
Fsu =	39000	PSI	r2 =	0.0000	IN
epu =	0.067	IN/IN	jm =	1.00	
epuLT =	0.030	IN/IN	te =	0.500	IN
tw =	0.310	IN	tb =	0.307	IN
e =	1.267	IN	a =	1.770	IN
b =	2.440	IN	h =	2.088	IN

Wall Tension Analysis:

Anet =	1.846	IN^2	ftw =	3228	PSI	eta =	1.000	
Agross =	1.846	IN^2	Rtw =	0.048	(Actual)			

Wall Bending Analysis:

			Kwall =	1.803		CU =	1.248	IN
I =	0.649	IN^4	Fbw =	116247	PSI	CL =	0.676	IN
mu =	3525	LB-IN	Mu =	60428	LB-IN	c =	1.248	IN
			Rbw =	0.058	(Actual)			

Wall Bending & Tension Interaction: ***** PLASTIC BENDING ANALYSIS *****

n =	1.25	Rtwu =	0.490	(Allowable)	
gamma =	0.915	Rbwu =	0.591	(Allowable)	
				MSwall =	9.17

End Pad Bending Analysis: ***** PLASTIC BENDING ANALYSIS *****

K3 =	0.591	fbe =	15038	PSI		
		Fbe =	91844	PSI		
Kend =	1.500				MSepb =	5.11

End Pad Shear Analysis:

fse =	3620	PSI		
			MSeps =	9.77

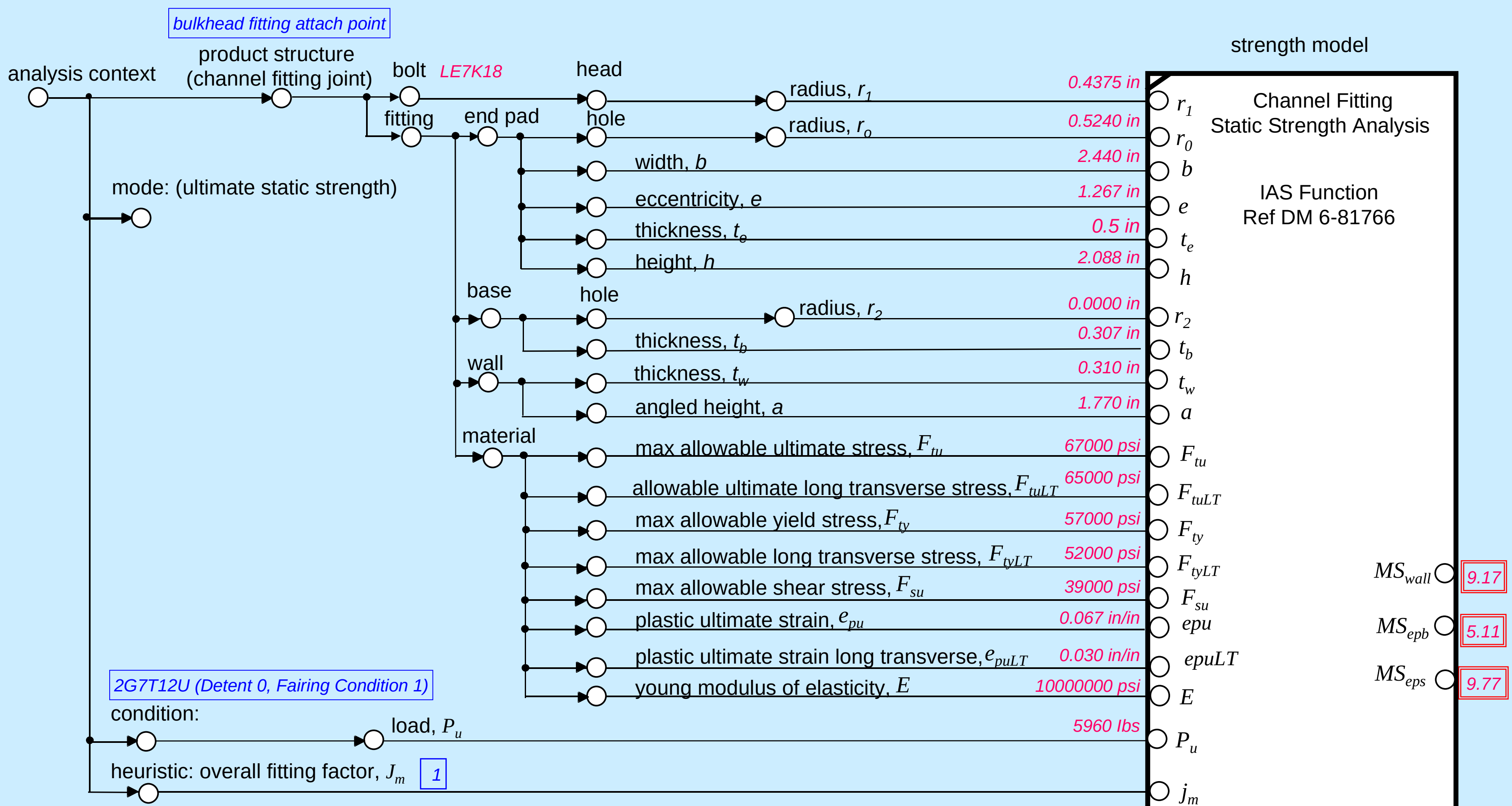
Allowable Load: Pallow = 36395 LBS

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	129 -300
CHECK						
APR						
APR						PAGE 206
PGM	s734c07-PROD	IAS				

CBAM Instance for Channel Fitting Analysis



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		

Fitting Analysis
Using COB-based CBAMs

channel_fitting_end_pad_bending_model_a

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

Solve

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

Outline

- Analysis Integration Challenges
- Introduction to Constrained Objects (COBs)
- Overview of COB-based XAI
- Example Applications
  - Electronic Packaging Thermomechanical Analysis
  - Aerospace Structural Analysis
- Summary ⇐

Analysis Integration Summary

- Strong emphasis on X-analysis integration (XAI, DAI)
- Multi-Representation Architecture (MRA)
  - Addressing fundamental XAI issues
    - » Explicit representation of design-analysis associativity
  - General methodology --> Flexibility & broad application
- Relevant experience and advances
  - TIGER / ProAM product data-driven analysis (STEP AP210, etc.)
    - » Demonstration engineering service bureau (at Atlanta ECRC)
  - Object techniques for next generation aerospace analysis systems
- Research, applications, and technology transfer
  - Analysis integration toolkit: *XaiTools*
  - Engineering information systems solutions
- Industry & government collaboration

For Further Information ...

- EIS Lab web site:
  - http://eislab.gatech.edu/
  - Publications, project overviews, etc.
  - See Publications, DAI/XAI, Suggested Starting Points