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AUTOMATING ROUTINE ANALYSIS IN ELECTRONIC PACKAGING USING PRODUCT MODEL-BASED ANALYTICAL MODELS (PBAMS), PART II: SOLDER JOINT FATIGUE CASE STUDIES

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ABSTRACT

A new representation of engineering analysis models, termed *product model-based analytical models* (PBAMs) was introduced previously [Peak and Fulton, 1992b]. Since PBAMs link analysis information with detailed design information, they enable rapid, flexible analysis in support of product design.

This document, Part II of two companion papers, describes PBAMs of representative solder joint fatigue models that illustrate and evaluate the PBAM representation. Part I overviews the PBAM representation and defines the constraint schematic notation used in this paper.

Results show that PBAMs provide rapid analysis results from mixed formula-based and finite element-based analysis models. In some cases different input/output combinations can be run; hence, both design analysis and limited design synthesis can be supported by the same PBAM.

1 INTRODUCTION

A new representation of analysis models, termed *product model-based analytical models* (PBAMs), was introduced earlier [Peak and Fulton, 1992b] which automates some analysis tasks to support product design. That paper defined generic analytical building blocks and described an initial PBAM of Engelmaier's solder joint fatigue model [Engelmaier, 1983, 1989].

The formal structure and operation of the PBAM representation is contained in more recent work [Peak, 1993]. This paper is largely extracted from that work and presents solder joint fatigue case studies which evaluate and illustrate the PBAM representation. The purpose of this paper (Part II) and its companion (Part I) is to show how the PBAM representation enables automated interaction of diverse analysis models and the product model. Part I discusses the concept of "routine analysis models" and gives an introduction to the general PBAM representation itself. It also defines the constraint schematic notation used later in this Part.

This paper reviews the solder joint fatigue analysis models by Engelmaier [1983, 1989] and Lau, et al. [1986] used as case studies. The specific PBAMs that were developed are discussed along with representative design scenarios using these PBAMs.

Nomenclature

$\overline{N}_f$	average cycles to failure
$\Delta\varepsilon^p$	plastic cyclic strain range
c	fatigue ductility exponent
ε_f'	fatigue ductility coefficient
$\overline{T}$	mean cyclic temperature, (ºC)
f	load frequency, (cycles/day, $1 \le f \le 1000$)
$\overline{T}_{sj}$	mean cyclic solder joint temperature (°C)
$\Delta\gamma_{sj}$	solder joint shear strain range
F	adjustment factor
$\Delta(\alpha\Delta T)$	steady state thermal expansion mismatch
T_o	reference temperature
T_{ss}	steady state temperature
L	length
h	height
E	Young's modulus
ν	Poisson's ratio
α	coefficient of thermal expansion (CTE)
σ_Y	yield stress
λ	strain hardening coefficient
ω_c	component occurrence[1]
Ω_c	set of component occurrences, $\{\omega_c\}$
a	load yield factor
Subscripts	
pwa	printed wiring assembly (PWA)
pwb	(bare) printed wiring board (PWB)
c, s, sj	component, substrate/PWB, solder joint (e.g., E_c, E_s, E_{sj})

[1] The term **component occurrence** means the usage of a component at a specific physical location in a PWA [Peak and Fulton, 1992b]. It refers to a component-solder joint-PWB assembly. **Component** refers only to a device of a given part number which may occur many times on a given PWA. The unique identifier for an occurrence is a reference designator (e.g. R110) versus a part number (e.g. PN 99120) for a component .

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2 SOLDER JOINT FATIGUE CASE STUDIES

This section overviews how to analyze solder joint reliability using two analysis models chosen from the literature that were used as case studies. *The emphasis of this research is on general methods for representing such analysis models rather than on developing the analysis models themselves.*

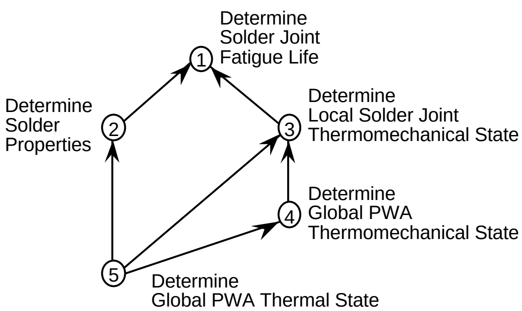


Figure 2-1 Major Steps in Solder Joint Fatigue Analysis

From a top-down viewpoint, the major steps required to predict the solder joint fatigue life for a given component occurrence are shown in Figure 2-1. Each step will now be discussed along with how it is carried out in the case study analysis models.

1. Determine Solder Joint Fatigue Life

The first part of this step is deciding what fatigue model to use. Since solder is a material with a relatively low melting point, its behavior is characterized by a low yield stress and by creep under relatively small loads. Therefore, Engelmaier [1983, 1989] uses the below modified Coffin-Manson relation for low cycle fatigue where the exponent, c, is frequency and temperature dependent (Step 2).

$$\overline{N}_f = \frac{1}{2}\left(\frac{\Delta\varepsilon^p}{2\varepsilon_f^{'}}\right)^{1/c} \tag{2-1}$$

The strain range, $\Delta\varepsilon^p$, must be found from the structure undergoing thermal loading (Step 3). Other fatigue models have been proposed which are usually more complicated and require different/further information (e.g. in [Lau, 1991]). Thus, this step drives what other analysis steps must be performed.

It is important to note that fatigue life prediction is a complex process requiring knowledge about many factors [Solomon in Lau, 1991, p. 446] which may be difficult to determine precisely for each PWA being designed. Furthermore, one must be aware of the statistical nature of fatigue failures and use fatigue life predictions resulting from relations like the above with caution.

2. Determine Solder Properties

Engelmaier [1983, 1989] developed the following relation for input into the above Coffin-Manson relation:

$$c = -0.442 - 0.0006\overline{T} + 0.0174\ln(1+f) \tag{2-2}$$

Note that some characterization of the thermal loads is needed, which Engelmaier provides by the following relation:

$$\overline{T} = \overline{T}_{sj} = \frac{1}{4}(2T_o + T_c + T_s) \tag{2-3}$$

The other property is constant for solder, $\varepsilon_f^{'} \approx 0.325$.

3. Determine Local Solder Joint Thermomechanical State

Since *the component and board are themselves complex assemblies of different materials*, one must decide how much detail to include in the analysis model. Modeling decisions such as which bodies to include and what types of loads to consider are made at the analysis system level. Within each major body in the analysis system, the level of geometric, material, and behavior detail to be considered must be determined. Similar decisions must be made for each sub-body/region within a body if it is to be further decomposed.

Analysis model representations should also support *product variations* that impact analysis results. For example, different types of components can require different types of analysis models (e.g. leads on leaded components may need to be modeled).

Given such variations, one can appreciate that there are several possible "good" analysis models depending on the purpose of the analysis and the product values involved. One may require solving simple formulas while another may involve a complex finite element analysis solution. The former may be appropriate for early design comparisons while the latter may be better suited for detailed analysis later in the design process.

If the Coffin-Manson model is used in Step 1, then the goal of this step is to determine the strain range the solder joint experiences each load cycle, $\Delta\varepsilon^p$. Therefore, some measure of cyclic strain must be extracted from the thermomechanical state found in the analysis model. Figure 2-2 illustrates representative analysis models from the literature that vary in both regional resolution and complexity level. Models designated Levels 1-4 could all be used to determine the thermomechanical state of the component occurrence. The two models (Levels 1 and 3) used in the case studies that fulfill this step are described next.

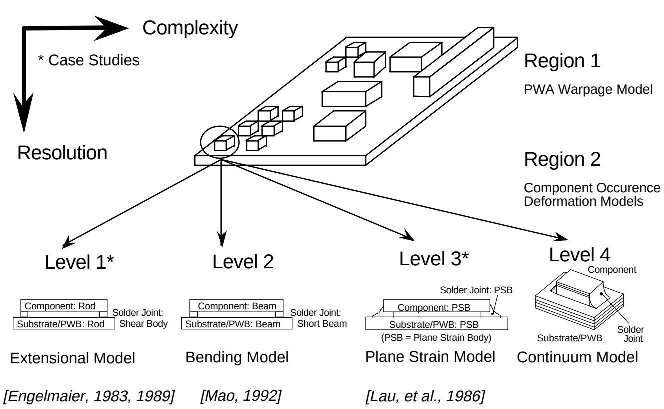


Figure 2-2 Varying Levels of Thermomechanical Analysis Models

Level 1: Extensional Model [after Engelmaier, 1983, 1989]

Engelmaier developed the following relations by assuming the solder joint is in a state of uniform shear strain (Figure 2-3).

$$\gamma_{sj} = \frac{L_c \Delta(\alpha \Delta T)}{2h_{sj}} \quad (2\text{-}4)$$

$$\Delta(\alpha \Delta T) = \alpha_s (T_s - T_o) - \alpha_c (T_c - T_o) \quad (2\text{-}5)$$

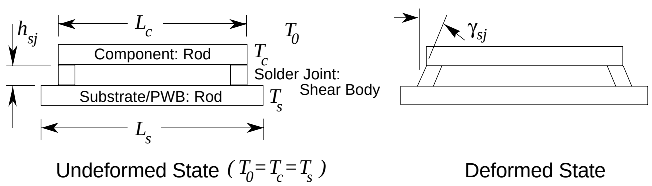


Figure 2-3 Level 1 Extensional Model [after Engelmaier]

At steady state the component and PWA are assumed to expand fully and unhindered as simple rods. It is assumed that the primary materials dominate the behavior of the component and PWB (modeled as homogenous bodies). These dominate materials (alumina for ceramic components and FR4 for PWBs) are assumed to be linear elastic (Table 2-1).

Table 2-1 Case Study Material Properties [Engelmaier, 1983; Lau, et al., 1986]

	E (psi)	ν	α (in/in-°C)
Alumina	37.0e6	0.30	6.7e-6
FR4	1.6e6	0.28	15e-6
Solder	1.5e6	0.40	21e-6
	σ_Y = 5000 psi, λ = 0.1		

The following relations slightly generalize Engelmaier's measure of worst-case distance between solder joints. Of course more precise relations could be developed based on detailed component geometry, but it is not clear if the model itself warrants such accuracy.

$$L_c = L_{total} \quad \text{a. discrete components} \quad (2\text{-}6)$$

$$L_c = \sqrt{L_{total}^2 + w_{total}^2} \quad \text{b. rectangular chip carriers}$$

Engelmaier bases the solder joint height on the following heuristic, where $t_{solder\ stencil}$ is the thickness of the solder stencil used to screen solder paste onto the PWB.

$$h_{sj} = \tfrac{1}{2} t_{solder\ stencil} \quad (2\text{-}7)$$

Thus, the solder joint height could be linked to the detailed design model of the actual solder stencil. Note that this analysis model does not consider the effects of conformal coating or the epoxy dot that typically secures a component if it is wave soldered.

Since it is assumed that strain is uniform in the solder joint and that plastic deformation dominates, the strain range needed by Step 1 is given by

$$\Delta\gamma_{sj} = F\left|\gamma_{sj}\right| \quad (2\text{-}8)$$

$$\Delta\varepsilon^p = \Delta\gamma_{sj} \quad (2\text{-}9)$$

where F is a correction factor based on experimental results. This factor depends on the type of solder joint per the following table (which is itself a discrete relation).

Table 2-2 Strain Range Correction Factor

Solder Joint Type	F [Engelmaier, 1989]
SMD chip	0.7 - 1.2
castellated leadless	0.7 - 1.2
columnar leadless	1.0 - 1.5
leaded	1.0

Level 3: Plane Strain Model [after Lau, et al., 1986]

The plane strain model (see Figure 2-2) was developed by Lau, et al. to study the effects of interconnection geometry on the solder joint fatigue of a surface mount chip resistor mounted on an FR4 PWB. Since more geometric detail is considered, a finite element-based solution is required. Solder is modeled as a bilinear kinematic hardening material [SASI, 1990] with properties given in Table 2-1. Figure 2-4 illustrates the parameters used to model solder joint geometry.

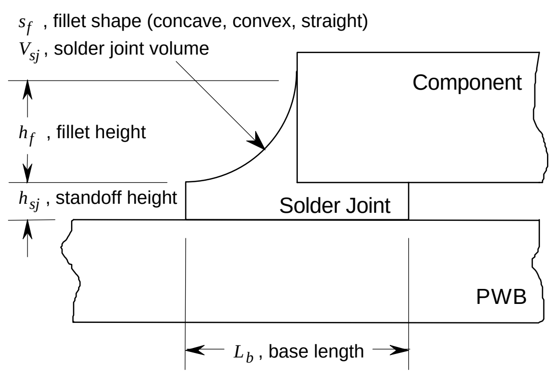


Figure 2-4 Solder Joint Geometry

In the present research the following extensions were made to the plane strain model to supplement Lau, et al.'s model. The primary intent of these extensions is to illustrate the capabilities of the PBAM representation.

a. To demonstrate how PBAMs can support different types of analysis modeling options, alternative models with linear elastic solder behavior and/or rectangular solder joint geometry are allowed.
b. Surface mount leadless components beyond just chip resistors are allowed. Hence, Eqn. 2-6b is also used to determine L_c.
c. To support different component lengths, the following simple relation was added.

$$L_s = 1.5 L_c \quad (2\text{-}10)$$

d. When the nonlinear solder option is chosen, the extensional model is used to estimate the initial load step in the finite element analysis. The load yield factor, *a*, is the factor by which the thermal load would be scaled to cause the solder joint stress to equal the yield stress. The details of the relation that determines *a* are given in [Peak, 1993] along with other solution method relations and variables.

As in the extensional model, the component and PWB are considered to be homogenous bodies consisting of their dominate material which are modeled with isotropic linear elastic stress-strain behavior (Table 2-1). Though no closed equation is known to exist for this analysis model and associated variations, it is still helpful to acknowledge the existence of the following relations. In fact, the input/output tuples obtained by running multiple FEA analyses with different values would be discrete relations in the truest mathematical sense [Bender and Williamson, 1991].

$$r_1(T_o, L_c, h_c, E_c, \nu_c, \alpha_c, T_c, L_s, h_s, E_s, \nu_s, \alpha_s, T_s, L_b, h_{sj}, E_{sj}, \nu_{sj}, \alpha_{sj}, T_{sj}, \gamma_{xy\ extreme,\ sj}, d) \quad (2\text{-}11)$$

$$r_2(T_o, L_c, h_c, E_c, \nu_c, \alpha_c, T_c, L_s, h_s, E_s, \nu_s, \alpha_s, T_s, L_b, h_{sj}, h_f, V_{sj}, s_f, E_{sj}, \nu_{sj}, \alpha_{sj}, \sigma_{Y,sj}, \lambda_{sj}, T_{sj}, \gamma_{xy\ extreme,\ sj}, d, n, a, e) \quad (2\text{-}12)$$

Eqn. 2-11 is for the case of rectangular solder joint geometry and linear elastic solder, while Eqn. 2-12 is for detailed geometry (Figure 2-4) and bilinear kinematic hardening solder. Note the inclusion of solution method parameters *d, n, a, e* since they affect the analysis results (*d* is a measure of mesh density, *n* is the number of load steps, and *e* is the convergence criteria).

Though other variables could be included in the above relations (e.g., fields of deformation, stress, and strain) it is the extreme total shear strain in the solder joint, $\gamma_{xy\ extreme,\ sj}$, that is of interest .

$$\Delta\gamma_{sj} = \left|\gamma_{xy\ extreme,\ sj}\right| \quad (2\text{-}13)$$

Though not explicitly stated, Lau and co-workers apparently adopted the above relation and Eqn. 2-9 (to provide input into the Coffin-Manson relation) by assuming that all strain becomes plastic strain at steady state.

The following list summarizes the information required by the plane strain model beyond that needed by the extensional model. The number of additional relations and variables is one measure of relative model complexity, along with what type of solution methods the relations require.

- Component and PWB geometry: h_c, L_s, h_s
- Solder joint shape: $L_b, h_{sj}, h_f, V_{sj}, s_f$
- Material properties: $E_c, \nu_c, E_s, \nu_s, E_{sj}, \nu_{sj}, \alpha_{sj}, \sigma_{Y,sj}, \lambda_{sj}$
- Initial load step estimator
- Solution method parameters: d, n, a, e

4. Determine Global PWA Thermomechanical State

This step would consider the interaction of components, solder joints, PWB board layers, and conductive traces that could cause the PWA to warp. The basic idea is to get warpage (out-of-plane deformation) and in-plane deformations from this global warpage model around the component of interest. These values then would be used as boundary condition inputs to the local model of Step 3 (Figure 2-2).

Yeh, et al. [1993] and Garratt [1993] have shown that the copper traces on a simplified bare PWB contribute significantly to global PWB warpage. However, for a realistic PWA, including the numerous conductive traces in a finite element model (along with component and solder joint details) most likely would make the model too large for solution. No known analysis model currently exists which considers such effects. Solomon [in Lau, 1991, p. 438] refers to work by others that determined the magnitude of PWA bending likely to occur.

To test how global/local models could be represented as PBAMs, an analysis model for PWA warpage was developed conceptually in this research at a high-level information input/output level [Peak, 1993]. Only the PWA design information that would be needed along with the information interfaces between this global model and the local model (Step 3) were considered. Hence, this paper contains numeric results only for the case where warpage effects are neglected.

5. Determine Global PWA Thermal State

For the case study analysis models, the goal of this step is to determine the spatially averaged component and PWB temperatures under the given thermal loading conditions.

Two basic types of thermal loads are considered that are relevant to solder joint fatigue [Engelmaier, 1989, 1983]:

A. *Uniform Thermal Cycling:* This load can result from daily temperature cycles experienced by products in non-climate-controlled environments such as outside or in a warehouse. No analysis model is needed if Steps 2, 3, and 4 only require steady state conditions since the following equation will hold.

$$T_c = T_s = T_{ss} \quad (2\text{-}14)$$

B. *Power Cycling:* Turning on and off a personal computer everyday is perhaps the most familiar example of this type of load. Before the product is turned on, the whole PWA is typically at a uniform temperature, T_o. After it is turned on, a temperature difference between the component and the PWB will typically exist, causing strain in the solder joint even if the CTEs are perfectly matched [Engelmaier, 1983].

Information about PWA electrical circuitry, thermal properties, the enclosure thermal environment, etc. (collectively contained in the PWA occurrence, ω_{pwa}) are needed to define the thermal analysis model. The following conceptual relation is part of this model, which typically would be solved approximately using a tool such as Autotherm [MGC, 1991]).

$$r(T_o, \omega_{pwa}, \omega_c, T_c, T_s) \quad (2\text{-}15)$$

The plane strain model by Lau, et al. only considered the steady state thermal cycling case (from -55ºC to 125ºC, as in automobile under-the-hood conditions [Engelmaier, 1989]), so their model required no thermal analysis. In this research power cycling was also applied to the plane strain model by estimating the uniform solder joint temperature as follows:

$$T_{sj} = \tfrac{1}{2}(T_c + T_s) \quad (2\text{-}16)$$

3 SOLDER JOINT FATIGUE CASE STUDIES

This section shows how PBAMs were developed and implemented for representative analysis models described in Section 2. Test runs with representative datasets are included.

Multiple PBAMs were developed to represent the case study analysis models. Figure 3-1 (which replaces Figure 3.9 in [Peak and Fulton, 1992b]) is an EXPRESS-G information model showing the relationships between these PBAMs and the analytical building blocks they utilize. This view is derivable from the master views of each PBAM. These PBAMs correspond with the analysis steps in Figure 2-1 as highlighted here in reverse step order (bottom-up).

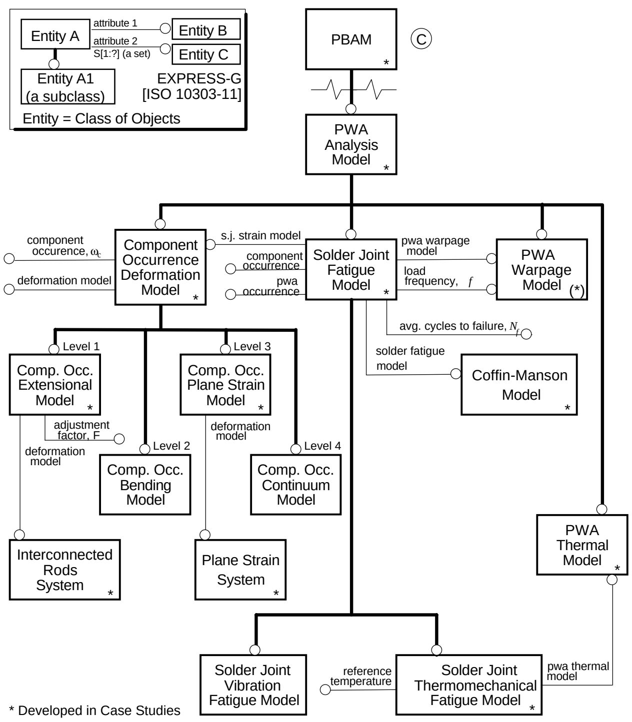


Figure 3-1 EXPRESS-G View of PWA Analysis Models

STEP 5 The PWA Thermal Model is a PBAM that provides component and substrate (PWB) temperatures when a PWA is under operational (i.e., powered) loads.

STEP 4 The PWA Warpage Model PBAM would provide global warpage values into the local deformation model of Step 3. It was developed as an extension at a conceptual level only [Peak, 1993] and is not included in this paper.

STEP 3 The Component Occurrence Deformation Model is an *abstract* PBAM. Abstract means that one of its subclasses can be instantiated for use, but it cannot itself [ISO 10303-11]. Figure 3-1 shows four models of varying complexity level (1 through 4 per Figure 2-2) that determine deformation in a component-solder joint-PWB assembly (a component occurrence). All four models are subclasses of this abstract class which was developed to capture the information these deformation models have in common. To date, the Level 1 and 3 PBAMs have been developed as case studies

LEVEL 1 The Component Occurrence Extensional Model (a.k.a. the Extensional Model) is a PBAM that represents component occurrence deformation behavior, where the component and PWB are modeled as rods. Thus, this PBAM includes the relations in Engelmaier's model that determine solder joint strain under thermomechanical loads (as well as other relations).

LEVEL 3 Component Occurrence Plane Strain Model (a.k.a. the Plane Strain Model). This PBAM performs the same function as the preceding PBAM, except all parts are modeled as bodies with plane strain behavior. Since this PBAM also allows different solder stress-strain behaviors and varying solder joint geometry detail, it represents a generalized version of the strain model by Lau, et al. Step 1 below discusses how a solder joint fatigue PBAM uses these two PBAMs.

STEP 2 Solder property determination is described next.

STEP 1 The Solder Joint Thermomechanical Fatigue Model (SJTF Model) is a special type of the Solder Joint Fatigue Model. It wraps and connects the above PBAMs to predict solder joint life under thermomechanical loads. It takes the temperatures from the thermal PBAM and processes them for input into the Coffin-Manson Model which determines the solder properties (STEP 2). It also links the strain determined by either of the above deformation PBAMs into the Coffin-Manson fatigue relation. Finally, the fatigue life can be output if the load frequency and component occurrence are input (with respect to a design verification input/output viewpoint).

One challenge of representing the analysis models is determining where to put each relation and the data it utilizes. Generally, one should balance complexity against grouping relations that are associated with each other. Relations that are likely to be used repeatedly as a group can be broken out from an otherwise associated larger group. One should also place relations at the correct level of generality. Finally, one must keep in mind that some of the information used by the PBAMs also is needed by other design and analysis tasks (e.g. component selection [Peak and Fulton, 1992a]). Therefore, the proper representation of this information to support such heterogeneous utilization is important to a flexible and extendible design environment.

Examples of how such guidelines were applied in the case studies is included in the following descriptions of the three major PBAMs. Supporting analytical primitives and systems used for the case studies are included in [Peak and Fulton, 1992b]. The reasoning behind the placement of each relation will now be discussed.

Solder Joint Thermomechanical Fatigue Model (SJTF Model)

This PBAM is capable of determining leadless component solder joint fatigue life under power cycling and elevated thermal cycling. The Solder Joint Fatigue Model superclass contains information that would also be common to the Solder Joint Vibration Fatigue Model shown in Figure 3-1.

Figure 3-2 shows the SJTF Model in an instance view (see Table 3-1 in Part I) which has been annotated to show where a few example equations are represented. A bold border

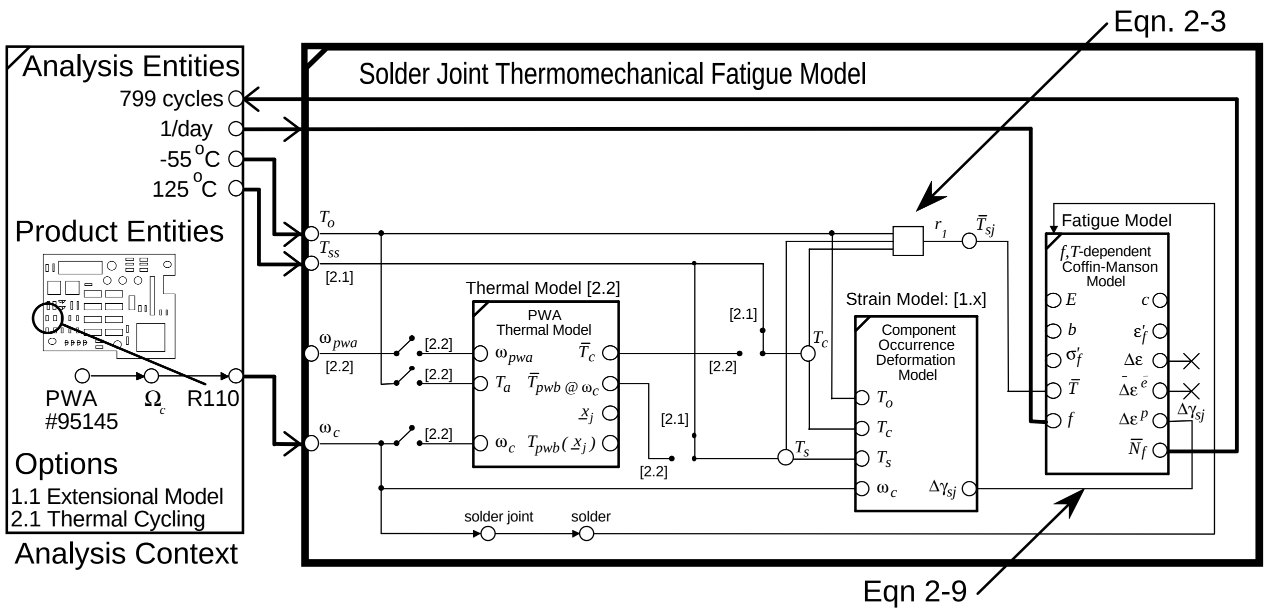


Figure 3-2 Solder Joint Thermomechanical Fatigue Model Instance View

surrounds the constraint schematic of this PBAM, which is an example of a complex PBAM. The analysis context specifies the PBAM options (described below). The values in the analysis context show how a specific example product entity (R110) and analysis entities (frequency, reference temperature, and steady state temperature) can be connected to the PBAM as inputs (indicated by the arrow directions). After that, the fatigue life, $\bar{N}_f$, is automatically determined as an output.

The major steps required in a solder joint fatigue analysis are represented by the three subsystems shown: Thermal Model (Step 5), Strain Model (Step 3), Fatigue Model (Steps 1 & 2). These subsystems and connections will be described now from the point of view of Figure 3-2 where fatigue life is the output. This figure shows sample product and analysis entities for the case of thermal cycling and Extensional Model usage (Case #1 - see Table 3-1).

The analysis context specifies the desired type of thermal load as an option in the SJTF Model (option category 2 in the Figure 3-2). In the case of thermal cycling, the "switches" are in the [2.1] position as shown, and the subsystem labeled Thermal Model is bypassed since Eqn. 2-14 applies. If the power cycling option were selected, the "switches" would be in the [2.2] position, and the Thermal Model would determine the component and PWB temperatures via Eqn. 2-15.

In either case the SJTF Model connects these temperatures directly to the Strain Model. Since Eqn. 2-3 is specific to the SJTF Model, it is represented as relation r_1 therein and transforms the temperatures for input to the Fatigue Model.

This PBAM could be considered a generalized version of Engelmaier's full fatigue model since the subsystem labeled Strain Model can be the Extensional Model (as in his model) or the more complex Plane Strain Model. Originally the Extensional Model and the SJTF Model were one PBAM (the PWA Two Rod Model in [Peak and Fulton, 1992b]). Since determining the strain in a solder joint is a relatively major step in the overall fatigue analysis process, that original PBAM was split into the two current PBAMs. This split became even more advantageous when the Plane Strain Model was added; otherwise, another PBAM, e.g., a PWA Plane Strain Model, would have been needed. Instead, the current approach was adopted to limit the complexity contained in any one PBAM and to increase modularity. Thus, the SJTF Model has an option category to specify the deformation model used. This situation is an example of **component substitution** (Table 3-1 in Part I) and is indicated by the [1.x] label in the constraint schematic. As indicated in the analysis context, the Extensional Model (option 1.1) is used in this particular instance view.

The Strain Model determines the solder joint strain range, $\Delta\gamma_{sj}$. Note that the SJTF Model connects this variable to the Fatigue Model by representing Eqn. 2-9 as a simple equality relation (a solid line). The Fatigue Model then uses the frequency, f, to finally determine the fatigue life, $\bar{N}_f$.

Eqn. 2-1 is captured as a relation in the Coffin-Manson Model class which can be used for applications other than just solder joint fatigue. A Coffin-Manson Model can be associated with all materials for which it is applicable. Since Eqn. 2-2 and the value for ε_f' are specific to 60%Sn-40%Pb and eutectic solder, they are stored in representations of those solders. Another PBAM could be developed to wrap the generic Coffin-Manson Model, just as the Level 1 and 3 models wrap their generic analytical systems; however, the small number of connections to the Fatigue Model did not seem to warrant an extra PBAM.

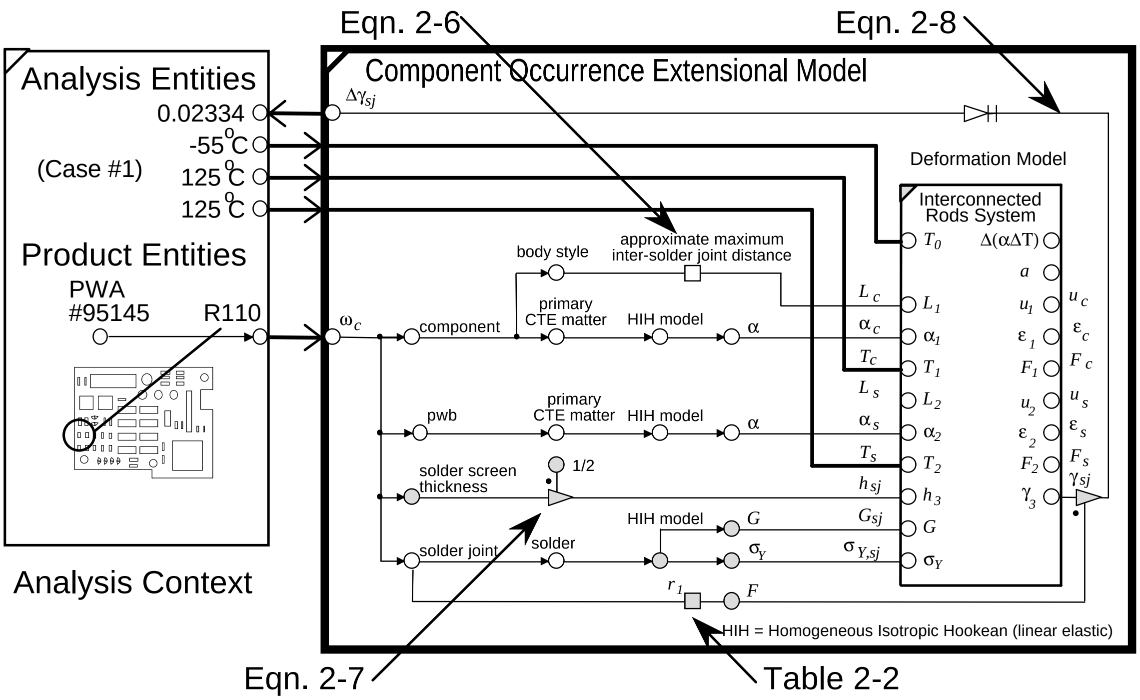


Figure 3-3 Extensional Model Instance View

Component Occurrence Extensional Model (Level 1)
Figure 3-3 gives an instance view of this simple PBAM which uses the Interconnected Rods System given in Part I as its Deformation Model subsystem. Basically the PBAM connects product variables in a component occurrence (e.g. R110) to the analytical variables in the generic Interconnected Rods System. For example, Eqn 2-6 is represented in the constraint schematic as labeled in the figure. Eqn. 2-7 is represented similarly as indicated. The component occurrence is asked for the solder stencil thickness since it would know the manufacturing process from which to request the desired information; however, since such manufacturing objects are not supported in the current implementation, the solder stencil thickness is a variable in the Component Occurrence class.

The Interconnected Rods System contains generic deformation relations in its constraint schematic (see Eqns. 3-1 & 3-2 and Figure 3-4 in Part I). The PBAM performs the semantic mappings from the application-specific relations (Eqns. 2-4 & 2-5) into these generic relations. For example α_c is mapped to α_1. Since analytical systems are "generic" components that can be used by many different PBAMs, this PBAM uses only some of the capabilities contained in the Interconnected Rods System. The material properties come from the component occurrence via product-analysis transformations contained in the Extensional Model.

Eqn. 2-8 changes the shear strain into shear strain range as represented by the scale & offset relation and the absolute value relation shown in series. This equation is an example of an analysis-analysis transformation in the Extensional Model. Since the adjustment factor, F, is experimentally determined specifically for this model (Table 2-2), it is contained in the scope of this PBAM.

Component Occurrence Plane Strain Model (Level 3)
The constraint schematic for this PBAM is given in Figure 3-4. Its subsystem, a Plane Strain Bodies System, is analogous to the Interconnected Rods System in the Extensional Model. It is this subsystem that contains the relations requiring FEA solutions (Eqns. 2-11 & 2-12).

Solder joint geometry variation is supported as option category 1 (as indicated by the switches in the figure), while category 2 is for the solder stress-strain model option. Note also the use of the Extensional Model as the Load Step Estimator subsystem when the nonlinear solder model option, [2.2], is chosen. Other relations are represented in a manner similar to that used in the Extensional Model.

3.2 Implementation of Case Study PBAMs

It is important to note that the PBAM representation of a given analysis model (the constraint schematic and other views) is itself largely independent of the implementation form. However, implementing PBAMs using objects and constraints appears to be the most natural form.

The PBAM data structure can be mapped very closely into an object-oriented language, as is true with the other product and analytical entities [Peak and Fulton, 1992b]. To implement relations as constraints, the prototype CAD/E framework described in the preceding paper was extended with an existing class library of general purpose constraints from ThingLabII

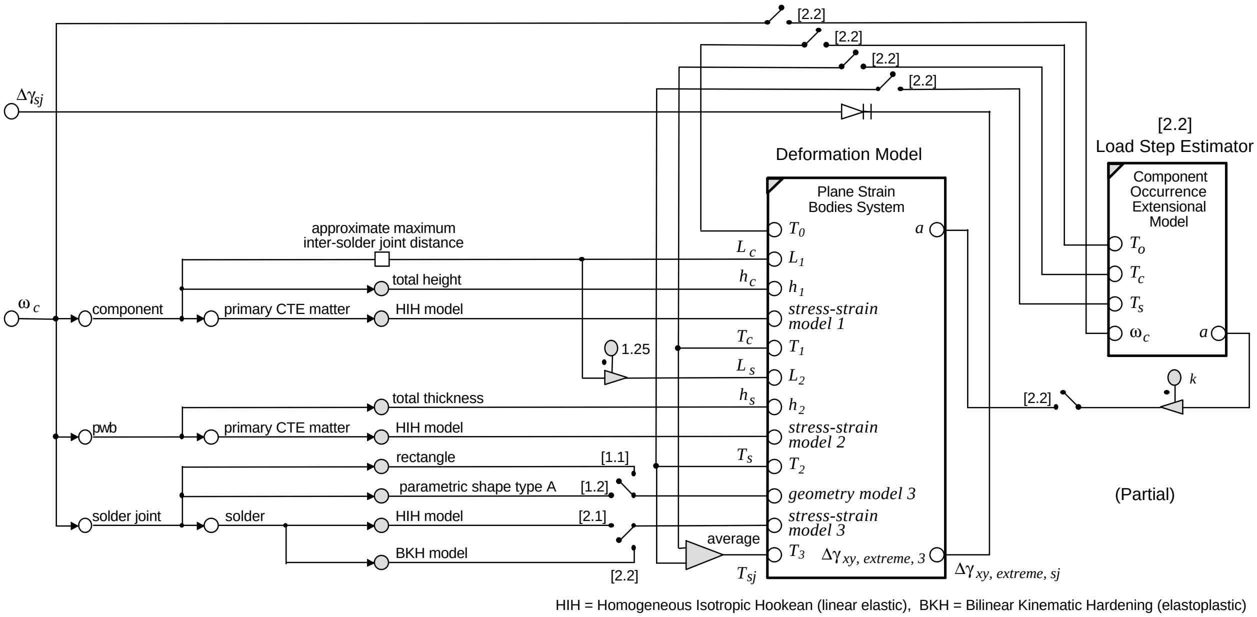


Figure 3-4 Plane Strain Model Constraint Schematic

[Maloney, 1991]. In this research some relations were implemented both with and without constraints [Peak, 1993].

Implementing relations requiring finite element-based solutions is just as easy as implementing formula-based ones from a purely constraint definition point of view. Relations among variables in the analysis can be captured in analytical system objects (e.g., the Plane Strain Bodies System in Figure 3-4). In this research parameterized ANSYS PREP7 models [SASI, 1990] were developed for this generic system (that could be used by applications other than solder joint fatigue). With this approach, each PREP7 parameter (including mesh density parameters, number of load steps, etc. if desired) would be related to variables in the constraint (but not necessarily with a 1:1 correspondence).

A method would be referenced in the constraint creation code (similar to above) for each desired output possibility. Each method can be implemented in the analytical system class that requires the finite element solution. Basically such methods transform the analytical system variables into the parameters needed by the ANSYS PREP7 file (or equivalent). Then that file is automatically created and submitted for solution until the result comes back and is returned by the method to the constraint. Thus, the constraint views a finite-element relation the same as any other relation. Practically, however, one should prevent the relation from reacting to every change in the constraint graph. This can be done, for example, by relaxing the relation until all its inputs have settled.

Before discussing results from actual test runs, the following implementation limitations should be noted (along with CAD framework limits given in [Peak, 1993; Peak and Fulton, 1992b]).

1. Only the Extensional Model has been implemented using constraints, while the Plane Strain Model remains in an earlier (pre-constraint concept) single I/O alternative form (i.e., it only goes in the direction of determining fatigue life as the output).
2. Nonlinear Cases #4 and #14 in Table 3-1 were run by manually supplying input to a parameterized ANSYS Prep7 file. The automatic creation and execution of this file from the Plane Strain PBAM would involve a procedure similar to that used in the linear cases.
3. A "black box" thermal model containing a few typical datasets was developed (i.e., the thermal analysis to obtain component and PWB temperatures was not actually performed in this system). Representative temperatures from Engelmaier [1983, 1989] were used.
4. The ANSYS results retrieval link parses the results file to extract only the stress and strain extrema in the solder joint. If desired, the full ANSYS results file could be loaded and stored as STEP FEA entities [ISO 10303-104] as previously demonstrated [Yeh, et al., 1991; Yeh, 1992].

3.3 Representative Design and Analysis Scenarios

Design Verification Scenario

With these limits in mind, a walk through of how these PBAMs actually run will now be given. Figure 3-5 illustrates the overall process from a software and hardware implementation point of view. The following describes the execution of each step to support a typical design/analysis scenario.

1. As discussed in Part I, a designer ideally would like to perform design verification checks as the design evolves. Here it is assumed that the components are being laid out on a PWA using a tool like BoardStation by Mentor Graphics. To check the solder joint reliability on this PWA, the designer selects a PBAM to use and specifies which

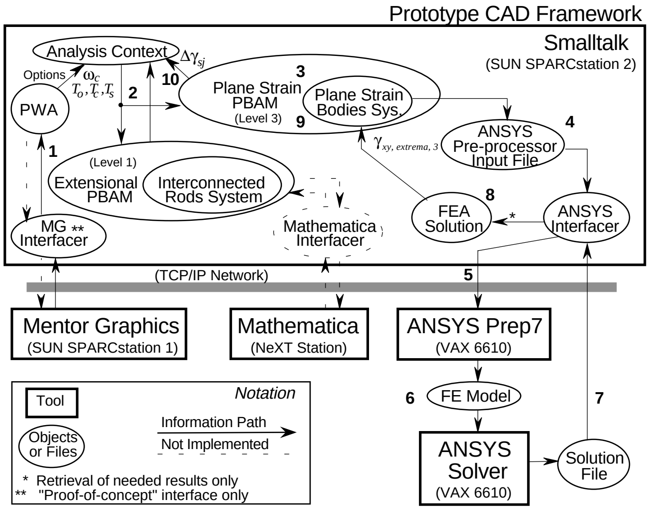


Figure 3-5 Implementation of PBAM Case Studies

components to check. The present PWA layout could be automatically transferred to the common database where the PWA object and related component objects have access to their other attributes that may not be used by Mentor Graphics (e.g., material properties and detailed geometry). The remaining steps are functional in the prototype.

2. To keep the figure from becoming even more cluttered, it is assumed that only the extreme solder joint shear strain range is to be determined (so only the Level 1 and 3 PBAMs for this purpose are shown). Effectively the designer is the analysis context in this scenario. He or she can specify the temperature conditions for the analysis and choose the component occurrence, ω_C, to be checked. Assuming the Plane Strain Model PBAM is selected, options for geometric and material detail can be specified. Finally, the designer tells the PBAM which I/O combination to use to get the maximum shear strain as output. No further user intervention is required.
3. With the above inputs, the Level 3 PBAM is ready to go. It instantiates a Plane Strain Body System and supplies it with needed data extracted and transformed from the component occurrence and temperature inputs (Figure 3-4). Then the PBAM asks this subsystem for the maximum shear strain in its interface body (the subsystem does not know that the interface body is a solder joint - the PBAM keeps track of that).
4. The subsystem knows that it needs to get the requested answer via a finite element solution, so it creates an ANSYS PREP7 input file [SASI, 1990] by filling in the appropriate blanks in a parameterized template. It then passes the results to the ANSYS interfacer.
5. This interfacer in turn transfers the file to a remote VAX and tells ANSYS to process the file.
6. The mesh generation, solution, and final results processing are performed by the ANSYS PREP7, solver, and POST1 modules respectively. At the expense of increased processing time, these phases can be displayed via X Windows if desired.
7. When ANSYS is done, the ANSYS interfacer retrieves the results.
8. After reading in the file, the interfacer calls an ANSYS parser to extract out the needed results (stress extrema in the linear solder case and total strain extrema in the nonlinear case).
9. The Plane Strain Bodies System gives the result requested (extreme strain in body 3) to the PBAM (after transforming the stress into strain, in the linear case).
10. Finally, the PBAM takes the absolute value of the result (Eqn. 2-13) since strain range was requested and gives the final result to the analysis context.

Thus, this PBAM implementation fully automates the creation, execution, and results feedback of a representative finite-element-based routine analysis model. The Level 1 Extensional PBAM is formula-based, so the constraint solver handles the relations in the constraint-based implementation. The earlier implementation without constraints [Peak and Fulton, 1992b] captures the relations in one-way methods. Conceivably one could forgo a constraint-based implementation; however, multidirectional interaction of many relations would become more complicated and inflexible (knowledge and control become intertwined).

Sample Results

Table 3-1 summarizes results from test runs using representative datasets. All cases in this table were done from a design verification perspective where reliability (fatigue life) was the product aspect being verified.

Some variations (geometric and material transformations) within the Plane Strain Model (Level 3) are included illustrating PBAM flexibility. Also two types of thermal loads are supported (Thermal Cycling and Power Cycling), demonstrating the use of PBAM Options.

Figures 3-6 and 3-7 illustrate representative results from the case study scenarios. Figure 3-6 shows Case #62 where the rectangular solder joint geometry option was selected. The

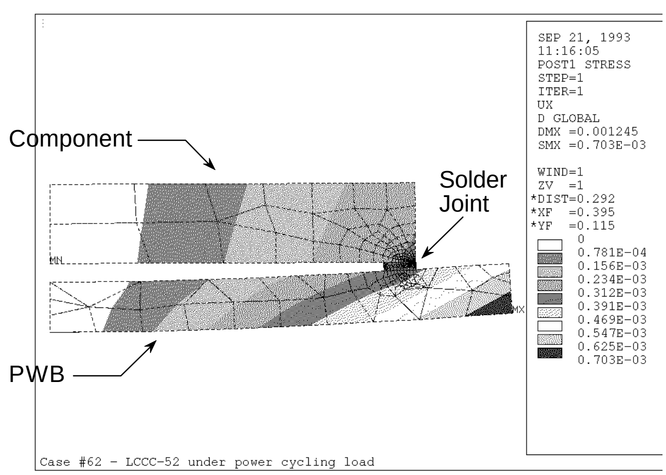
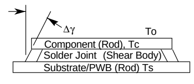
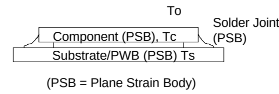


Figure 3-6 Deformations with Rectangular Geometry Option

Table 3-1 Solder Joint Fatigue Case Study Results

SJTF Model *Options* Strain PBAM	**Level 1** **Extensional Model** 		**Level 3** **Plane Strain Model** 					
Solder Model	Viscoplastic Solder Model		Linear Solder Model				Nonlinear Solder Model*	
Solder Joint Geometry	1D Solder Joint		Rectangular Solder Joint		Detailed Solder Joint		Detailed Solder Joint	
Scenario	$\Delta\gamma_{sj}$ (strain)	$\overline{N}_f$ (cycles)	$\Delta\gamma_{sj}$	$\overline{N}_f$	$\Delta\gamma_{sj}$	$\overline{N}_f$	$\Delta\gamma_{sj}$	$\overline{N}_f$
Thermal Cycling (h_{sj}=0.005", 0.062" FR4 PWB, T=-55 to +125 °C, f=1 cycle/day)								
1206 Resistor	#1 0.0233	799	#2 0.0270	578	#3 0.0098	5422	***#4 0.0119	3536
LCCC-52	#51 0.1716	9	#52 0.0483	159				
Power Cycling (h_{sj}=0.010", 0.062" FR4 PWB @ 88°C, T_O=20°C, f=1 cycle/day)								
1206 Resistor, T_c=89°C	#11 0.0043	25062	#12 0.0088	5467	#13 0.0036	36444	#14 0.0025	77105
LCCC-52, T_c=96°C	**#61 0.0293	399	#62 0.0167	1347				

* Not integrated in prototype (manually created ANSYS file). LCCC = leadless ceramic chip carrier

Published results: ** $\Delta(\alpha\Delta T)$= 511 ppm (exact match) [Engelmaier, 1983]

***$\Delta\gamma_{sj}$ = 0.0143, $\overline{N}_f$ > 2000 cycles (analysis), $\overline{N}_f$ > 885 cycles (experiment) [Figures 7 and 16 by Lau, et al. 1986]

detailed solder joint geometry option was selected in Case #3 as shown in Figure 3-7 (which is a linear version of Figures 7 and 16 by Lau, et al. [1986]).

Parametric Study / Design Synthesis Scenario

Table 3-2 gives results for the constraint implementation of the Extensional Model. The output variable was changed from the following baseline values used in Case #11. This type of I/O combination variation would commonly be encountered in a "what if" design scenario where the designer knows the target life the solder joint must meet and wants to see what factors can be changed to achieve that target life (e.g., solder joint height or PWB material properties). Thus, the target life becomes an input to the analysis (e.g., 20,000 or 40,000 cycles) and the parameter allowed to vary becomes the output.

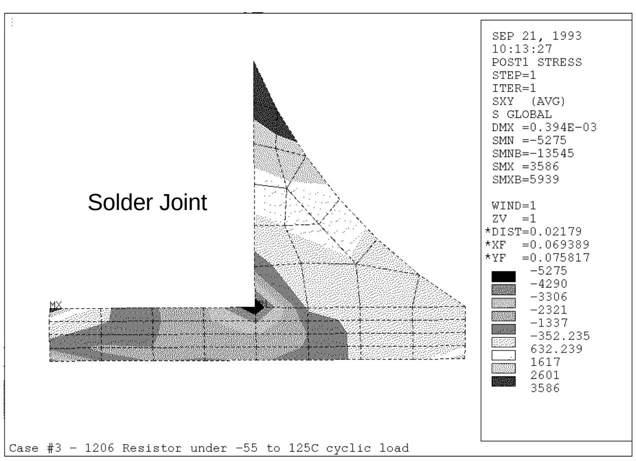


Figure 3-7 Shear Stress in Detailed Solder Joint

Baseline Parameters

PBAM: SJTF Model & Extensional Model (Level 1)
Conditions: Power Cycling, T_O=20°C, f =1 cycle/day
PWA: PN 95415
Component Occurrence: R109, 1206 SMD resistor,
PN 99120, L_c = 0.125, α_c = 6.7E-6 (in/in)/°C, T_c = 89°C
PWB: PN 99120, FR4, 0.062" thick, α_s = 15.0E-6 (in/in)/°C,
T_s = 88°C
Solder Joint: 60Sn 40Pb solder, h_{sj} = 0.010"

As could be expected, results show that an increased fatigue life can be achieved by increasing the solder joint height, h_{sj}. For example, Case #11.h.b determined that the solder joint height should be 0.012" to achieve a desired life of 40,000 cycles. Alternately, an increased fatigue life can be achieved in this case by selecting PWB materials with lower CTEs, α_s.

Table 3-2 Parametric Variation Using Constraint Implementation

Variation	$\overline{N}_f$ (cycles)	h_{sj} (in)	α_S ((in/in)/°C)
#11.baseline	***25062***	0.010	15.0e-6
#11.h.a	20000	***0.009***	15.0e-6
#11.h.b	40000	***0.012***	15.0e-6
#11.α_S.a	20000	0.010	***15.9e-6***
#11.α_S.b	40000	0.010	***13.4e-6***

Bold indicates output (result) for given variation on Case #11

If solder joint height is the desired output, the analysis result potentially can directly change the design due to the simple product-analysis transformation involved in this case (where solder joint height is assumed to be proportional to the thickness of the stencil used during manufacture). However, even here not just any stencil thickness can be chosen as they come in standard sizes. Also too thick of a stencil can cause solder bridging during manufacture.

Thus, the focus has been on getting the analysis result back to the point where it could be considered along with other variables in a design decision. Furthermore, once that design decision has been made, its impact can be rapidly accessed by re-running the same PBAM in different direction.

4 DISCUSSION

Strengths

1. Using the SJTF Model with the Plane Strain Model option shows how a PBAM enables interaction of formula-based and finite element-based analysis models. In the underlying constraint graph, the relations that the Plane Strain Bodies System contains are treated as any other relation. The fact that the relations require a finite element analysis solution is immaterial with respect to the structure of this PBAM. The interaction of this analysis model with other models in the SJTF Model constraint graph that have different solution methods naturally follows.
2. The parametric study example demonstrates how PBAMs can enable multidirectional analysis. Thus, analysis models interact in different directions, and "what if" design scenarios can be supported.
3. Obtaining fatigue life from the SJTF Model using the Extensional Model option takes less than a few seconds, while using the Plane Strain Model option requires around four minutes (depending on network and machine loads as well as selected options). Even with the Plane Strain Model option, only a few percent of the total time is spent creating the ANSYS PREP7 file and using the FEA results in the Coffin-Manson Model [Peak, 1993]. Hence, in these cases PBAMs provide relatively rapid analysis results where the speed is limited by the solution procedure rather than by model creation.
4. The Plane Strain Model options (different stress-strain models and varying geometric detail) demonstrate how PBAMs allow flexibility in analysis model complexity.
5. The analysis results in Table 3-1 re-emphasize the need to check solder joint reliability since fatigue poses a potentially significant problem. Thus, performing such analyses frequently and rapidly during design (which PBAMs enable) is helpful, if not essential.

Issues

1. For the same physical situation, the analysis results (Table 3-1) given by models with different options vary quite a bit (e.g., $\overline{N}_f$ in Cases #51 and #52 differs by an order of magnitude). These discrepancies call into question how appropriate the analysis model options are. However, these analysis models and added options still serve their purpose with respect to this research because their variety of features demonstrates the flexibility of the PBAM representation. The fact that a PBAM is only as good as the analysis model it represents is, nevertheless, a very important point which is highlighted here.
2. Limitations on input/output combinations are discussed in [Peak, 1993]. In brief, solution procedures must exist for each relation in the direction it will be run for a given I/O combination. Note that some solution procedures have natural I/O combinations. For example, in the Plane Strain Model FEA solution, variables such as component temperature are natural inputs while maximum solder joint stress is a natural output. Reversing the roles of these two variables would require a more expensive iterative solution procedure. Furthermore, some constraint solvers do not support I/O combinations requiring the solution of simultaneous equations.
3. The flexibility mentioned above in Item 4 raises the issue of how one decides which options are appropriate for a given analysis need. This issue is related to the limitations and assumptions of the analysis model itself which are beyond the scope of the current PBAM representation.
4. The case studies involve geometry that is relatively simple and can be parameterized. Similarly, the information exchanges between subsystems have been single discrete values (versus a time- or space-varying field of discrete or continuous values). It is felt that the main impact increased geometric complexity will have is the need for more complex product-analysis and analysis-analysis transformations. The current PBAM *structure* can already support such new transformations since it would represent them in the same way as any other relation. However, it is acknowledged that other unforeseen factors may impact the PBAM representation in this respect. unknown
5. All examples in this paper have had **predefined compositional topology**, i.e., the number of bodies that compose the model is known *a priori*. For example, both Level 1 and Level 3 models have four bodies (component, PWB, and two solder joints - but only one solder joint is modeled due to symmetry).

   Often analysis models have **postdefined compositional topology**, where the number of bodies involved is not known until a specific product instance is selected. For example, the PWA warpage model mentioned in Step 4 of Section 2 would typically model a different number of components for each different PWA analyzed. Currently the PBAM representation does not support postdefined compositional topology.

6. The Plane Strain Model provides one example of how some information is missing in analysis model descriptions. The paper by Lau, et al. [1986] did not include the length of the PWB section, the initial load step, or convergence criteria (not that such detail should be included) As discussed in Part I, such cases make it difficult to reproduce an analysis model exactly.
7. As seen in Section 2, existing analysis models may not consider some product variations of interest (e.g. components with epoxy dots or conformal coating). Thus, these case studies illustrate how the search for "routine" analysis models can help identify areas requiring further analysis model development.

5 SUMMARY

Product model-based analytical models (PBAMs) can fully automate the creation, execution, interaction, and (to some degree) the results feedback of a variety of routine analysis models. This paper has demonstrated some of the characteristics of the PBAM representation through solder joint fatigue case studies, including:

- Uniform treatment and interaction of analysis models requiring different solution methods.
- Multiple input/output alternatives.

The latter two points have been emphasized in particular, and results show that PBAMs provide rapid analysis results from mixed formula-based and finite element-based analysis models.

In conclusion, it is felt that developing and implementing PBAMs for these analysis models has served to validate the PBAM representation and demonstrate its usefulness.

ACKNOWLEDGMENTS

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