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An Inverse Approach to Identify the Constitutive Model Parameters for Crashworthiness Modeling of Aluminum Honeycombs and Moving Deformable Barriers (MDBs)

NCAC

FHWA/NHTSA National Crash Analysis Center

The George Washington University

An Inverse Approach to Identify the Constitutive Model Parameters for Crashworthiness Modeling of Aluminum Honeycombs and Moving Deformable Barriers (MDBs)

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OUTLINE

- Introduction
- Challenge
- Component Based Approach
- Full Scale Approach
- Conclusion

INTRODUCTION

- Movable Deformable Barriers (MDBs) are used in surrogate tests to represent the behavior of an average midsize vehicle.
- The main difficulty in MDB modeling is the prediction of frontal energy absorbing barrier, where honeycomb materials are used and usually expected to simulate complex failure modes.
- Finding Honeycomb material model parameters experimentally is a challenge.
- Inverse approach can be implemented for material model parameter predictions.
- Only component based inverse studies may not satisfy predicting the overall behavior.
- A coupled component based-full scale inverse approach is proposed to be more successful for highly non-linear crashworthiness studies.

CHALLENGE

❖ Implicit scheme is used for the entire component based models for 3s of runtime.

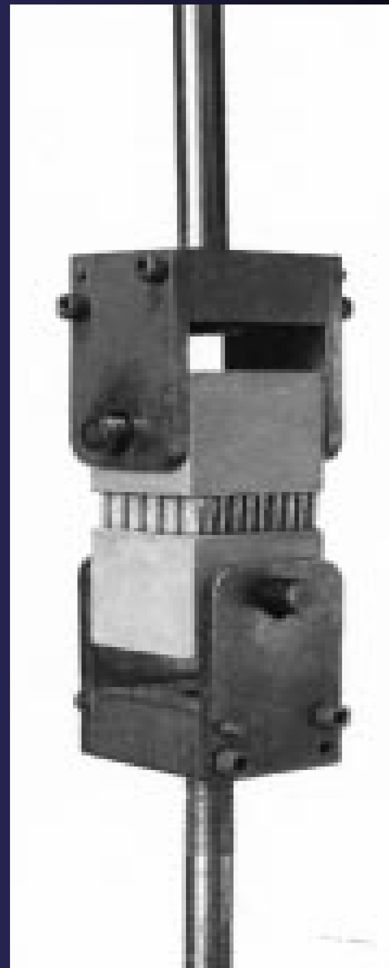
❖ Satisfying the robustness of the numerical model is a must for the upper and lower bounds of the independent variables.

❖ Coupling both implicit and explicit schemes for the same optimization problem.

❖ Full scale crash test is a challenge itself since it takes approximately 5 hours for each run. We have 10 independent variables for this full scale model.

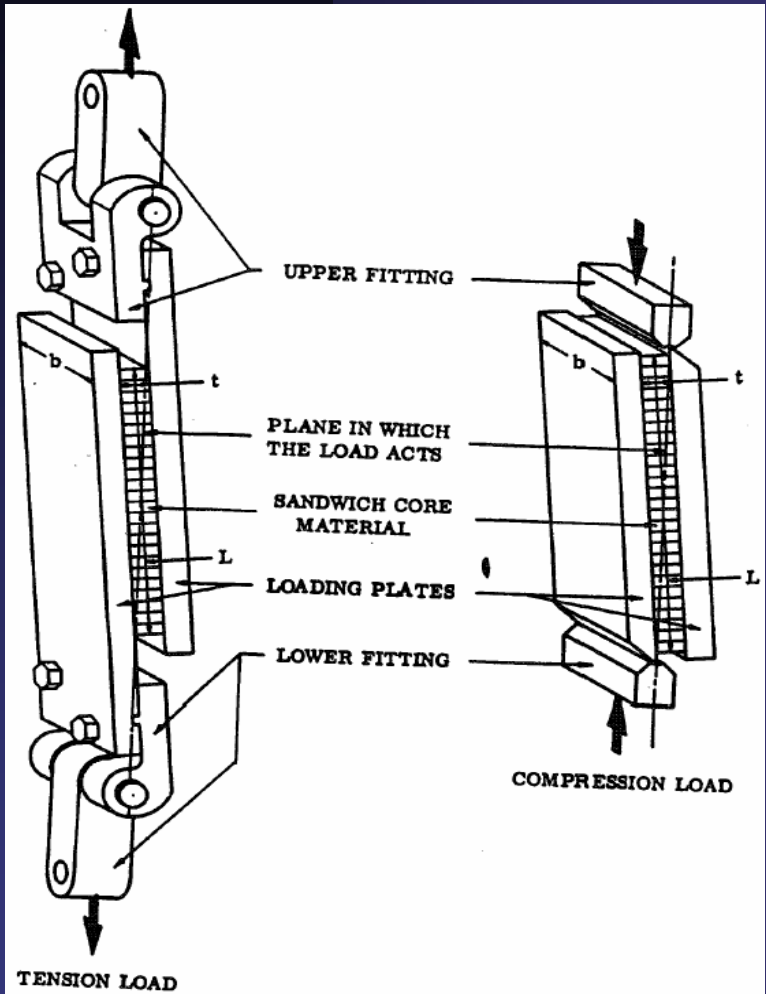
COMPONENT BASED APPROACH

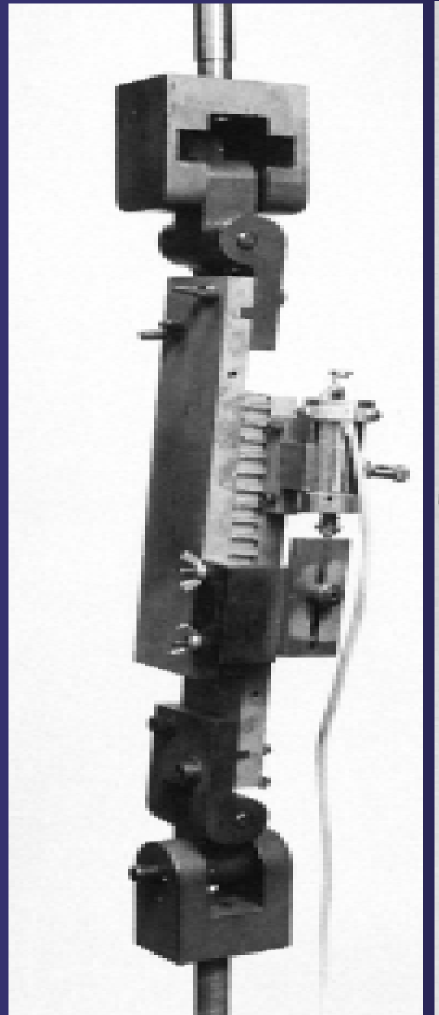
Compression Test Setup

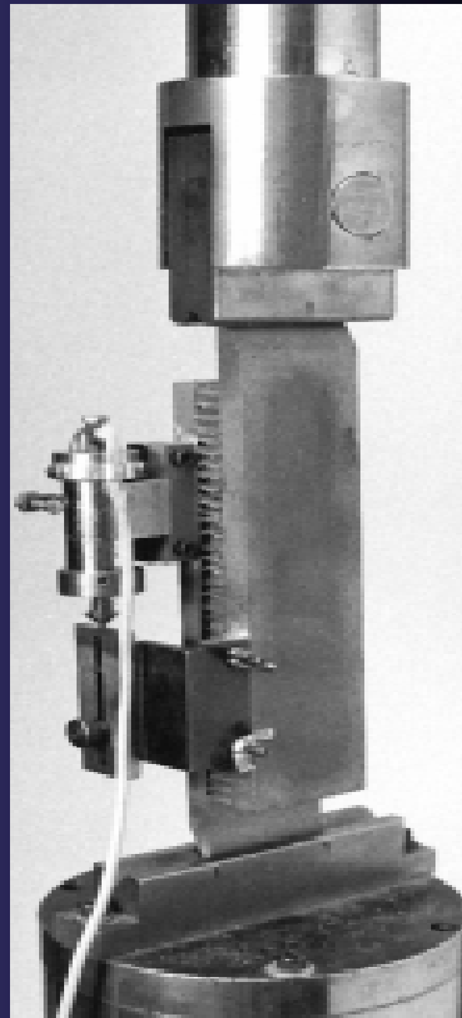


Tension

COMPONENT BASED APPROACH

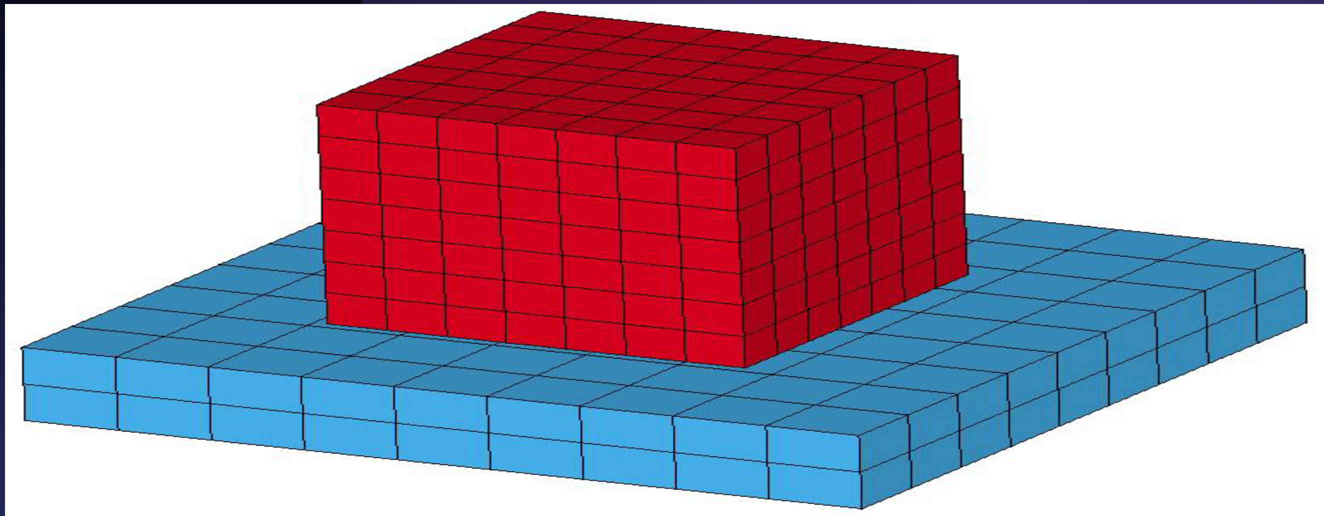


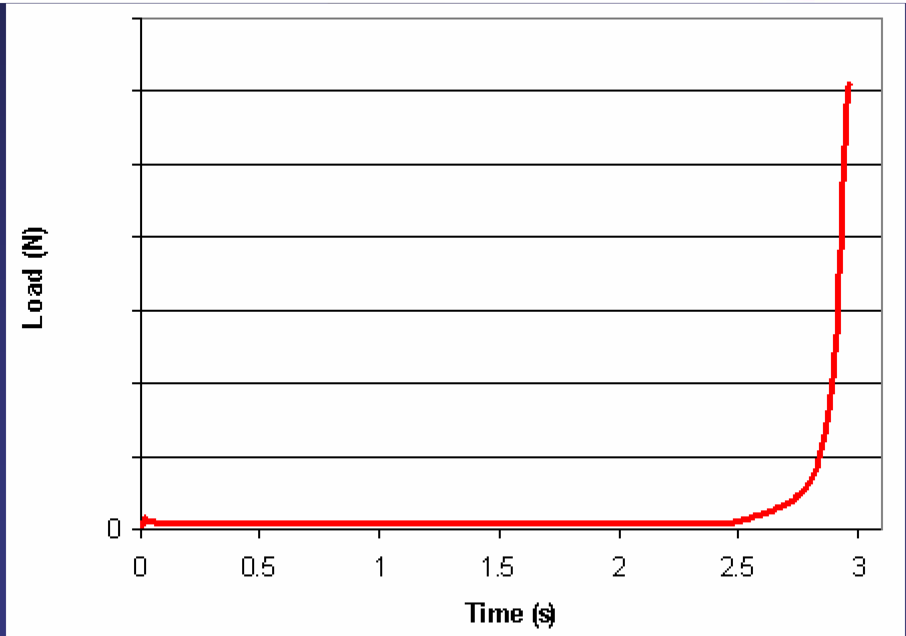




Compression-Tension Shear Test Setup

COMPONENT BASED APPROACH

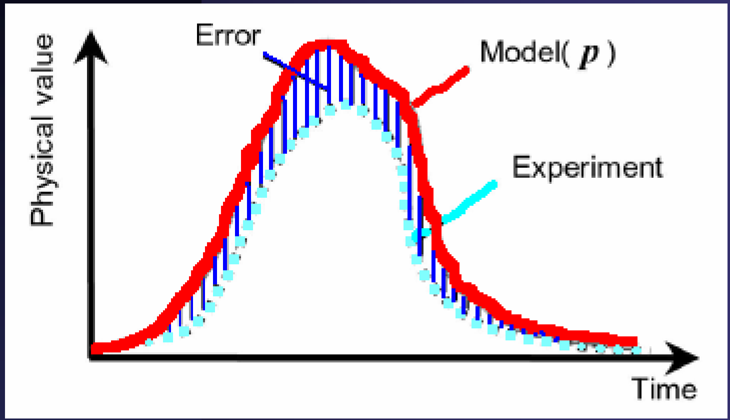


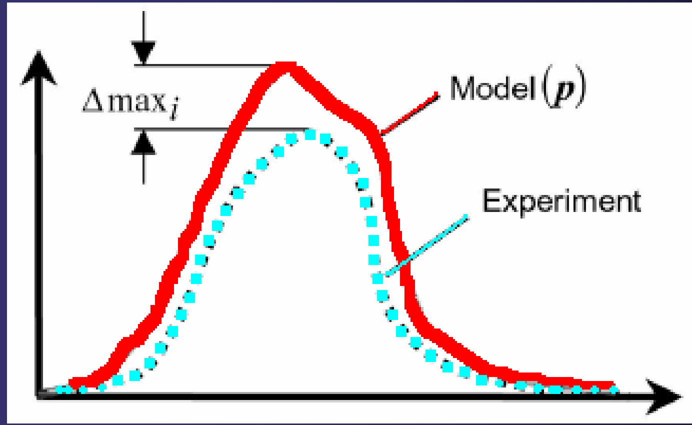


Compression Test Setup & Numerical Model

Courtesy of Plascore Inc.

COMPONENT BASED APPROACH





The Objective Function to be Minimized "Residual"

❖**The reaction force measured through the compression test is selected as the baseline response function.**

❖**The reaction force measured through the SPC ASCII output is selected as the simulation response function. (7 response points are selected)**

❖ **Minimizing the residual reaction force "Error" between the experimental and numerical data is the Objective.**

$$R(\boldsymbol{p}) = \left(\Delta \max_1 (\boldsymbol{p})^2 + \cdots + \Delta \max_7 (\boldsymbol{p})^2 \right)^{1/2} \rightarrow \min .$$

COMPONENT BASED APPROACH

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	E	PR	SIGY	VF	MU	BULK
Type	I	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	.05	0.0

Card 2								
Variable	LCA	LCB	LCC	LCS	LCAB	LCBC	LCCA	LCSR
Type	F	F	F	F	F	F	F	F
Default	none	LCA	LCA	LCA	LCS	LCS	LCS	optional

Card 3	1	2	3	4	5	6	7	8
Variable	EAAU	EBBU	ECCU	GABU	GBCU	GCAU	AOPT	
Type	F	F	F	F	F	F		

Design Variables

Assumption:
EBBU = ECCU
and
GAB = GCA

So, There are 6 Independent Variables

COMPONENT BASED APPROACH

Optimization Problem

$$R(\boldsymbol{p}) = \frac{1}{2}\|\boldsymbol{r}_m(\boldsymbol{p})\|_2 = \left(\mathrm{r}_1(\boldsymbol{p})^2 + \cdots + \mathrm{r}_m(\boldsymbol{p})^2\right)^{1/2} \rightarrow \min ,$$

$$\boldsymbol{r}_m(\boldsymbol{p}) = \begin{bmatrix} y_{\exp_1} - modelresponse(x_{\exp_1}, \boldsymbol{p}) \\ \vdots \\ y_{\exp_m} - modelresponse(x_{\exp_m}, \boldsymbol{p}) \end{bmatrix}, \quad \boldsymbol{p} = (p_1, \ldots, p_n) .$$

- **The Response Surface Method (RSM) is applied in order solve the optimization problem of minimizing the distances of experimental points to points calculated with a specific material model.**

- **This method has become popular for optimization studies involving the simulation of nonlinear dynamical problems.**

- **The purpose of the method is primarily to avoid the necessity for analytical or numerical gradient quantities as these are either too complex to formulate, discontinuous or sensitive to round-off errors. (Beneficial for crashworthiness)**

COMPONENT BASED APPROACH

- The objective of the parameter identification problem is to minimize the difference between the computational and the experimental results. Therefore, an objective function based on the well-known Least-Squares-Method is introduced:

$$R(\boldsymbol{p}) = \frac{1}{2}\|\boldsymbol{r}_m(\boldsymbol{p})\|_2 = \left(r_1(\boldsymbol{p})^2 + \cdots + r_m(\boldsymbol{p})^2\right)^{1/2} \rightarrow \min , \quad \begin{array}{lll} g_i(\boldsymbol{p}) \leq 0 & ; & i = 1,\ldots,k \ , \\ h_j(\boldsymbol{p}) = 0 & ; & j = 1,\ldots,l \ . \end{array}$$

$$\boldsymbol{r}_m(\boldsymbol{p}) = \begin{bmatrix} y_{\exp_1} - modelresponse(x_{\exp_1}, \boldsymbol{p}) \\ \vdots \\ y_{\exp_m} - modelresponse(x_{\exp_m}, \boldsymbol{p}) \end{bmatrix}, \quad \boldsymbol{p} = (p_1, \ldots, p_n) \ .$$

- Here, *m* specifies the number of experimental observations of any desired physical response value resulting from one or more boundary value problems. The Least-Squares functional is a function of the vector which contains n material parameters.

- These parameters are acting as design variables in the optimization process.

- In addition, sets of functions g_i and h_j may define inequality and equality constraints in order to bound the variation of the parameters.

COMPONENT BASED APPROACH

Point Selection Technique

❖D-Optimal Design is selected as the point selection algorithm for the approximate design space.

❖D-Optimality is known as one of the best methods that design regions of irregular shape and any number of experimental points.

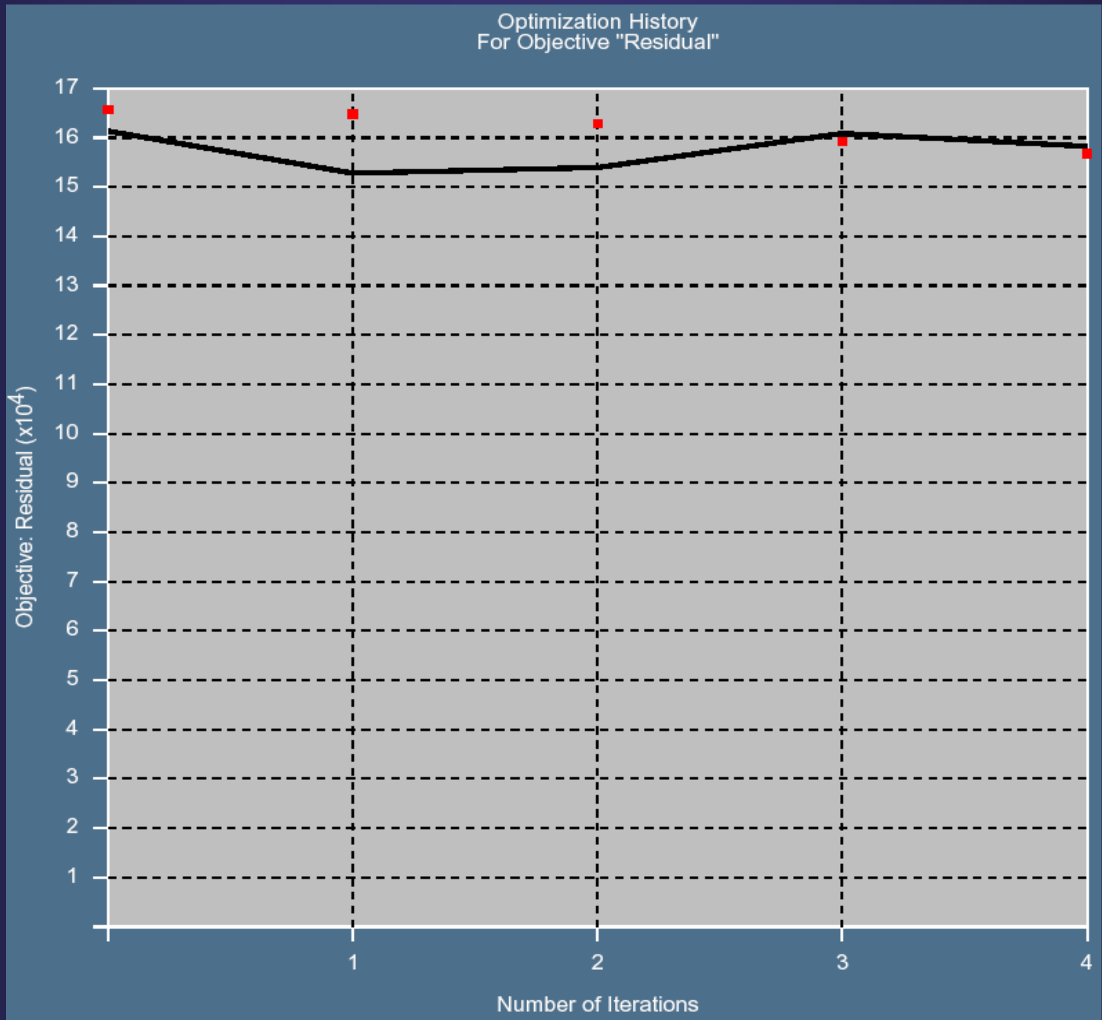
❖The experimental points for the D-Optimal Design are usually selected from a full factorial design by using the D-optimality criterion, which is basically a Genetic Algorithm.

❖The number of experimental points is of course in correlation with the order of the approximation functions.

❖In this study we compared Linear and Quadratic approximations.

COMPONENT BASED APPROACH

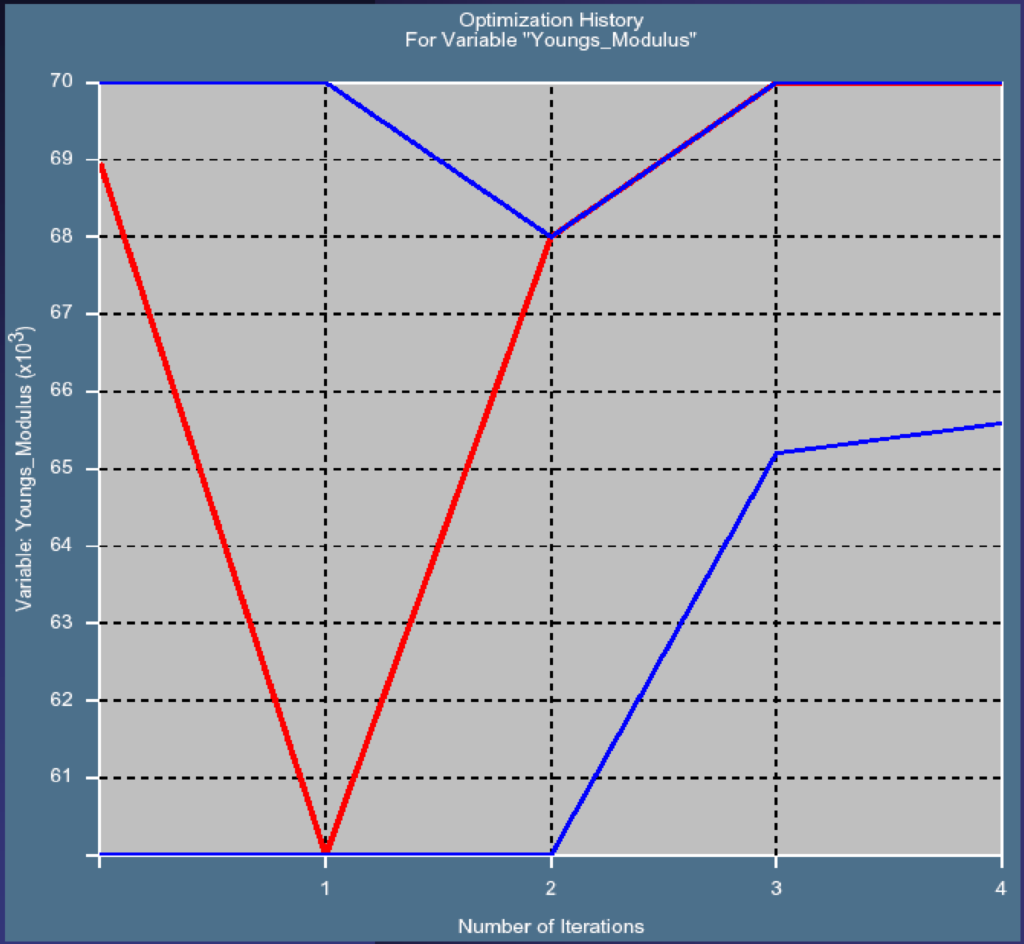
Results - Linear



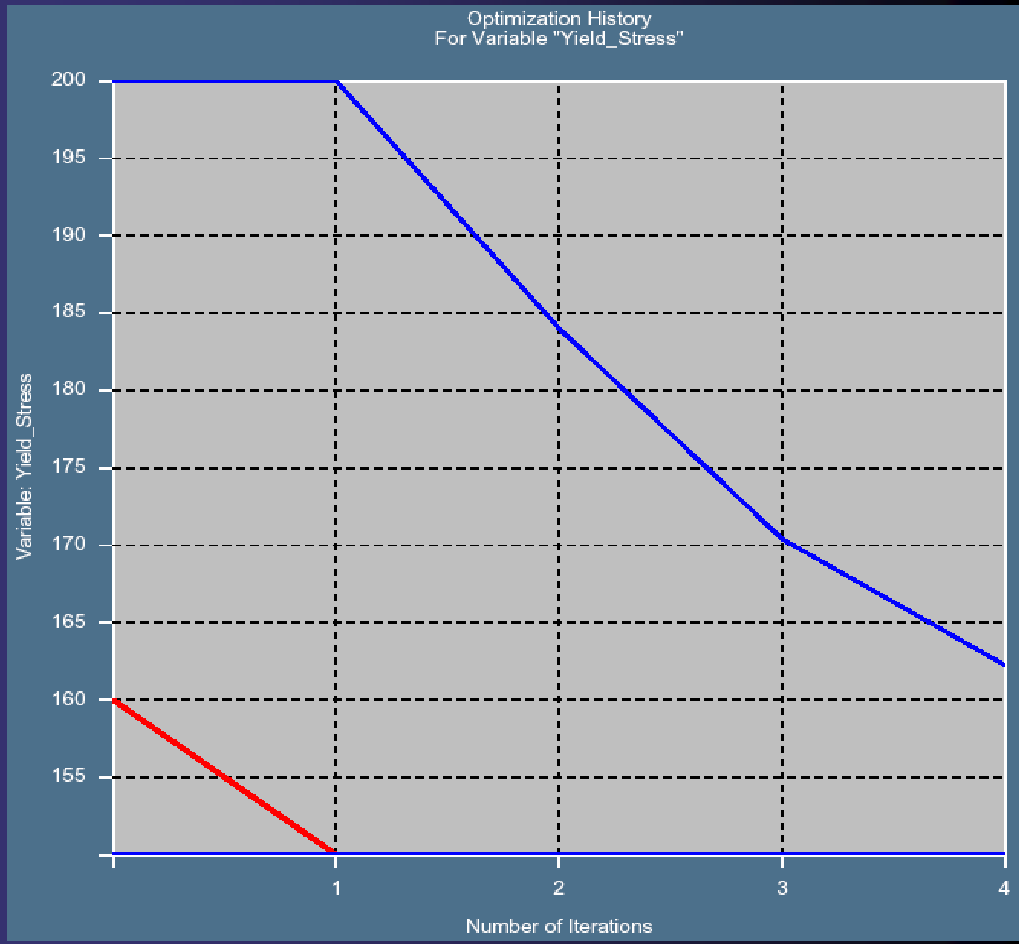
Convergence of Objective

COMPONENT BASED APPROACH

Results - Linear



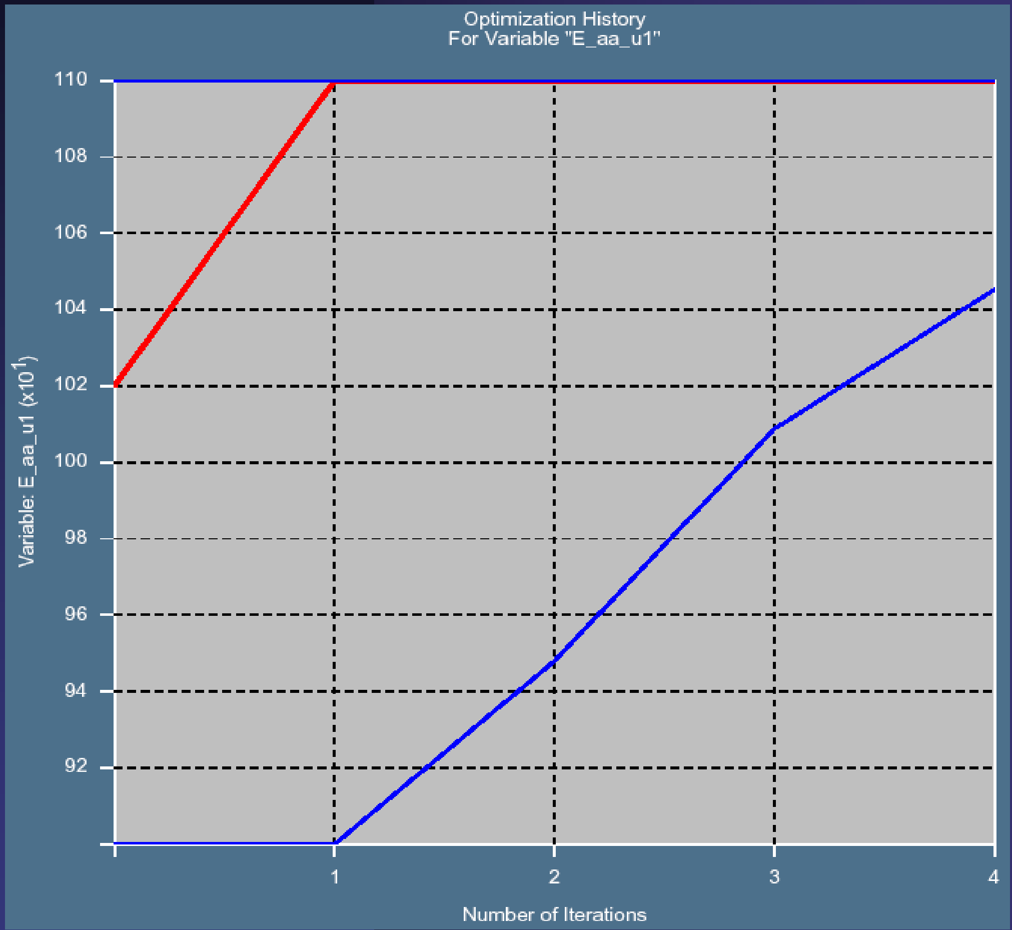
Young Modulus



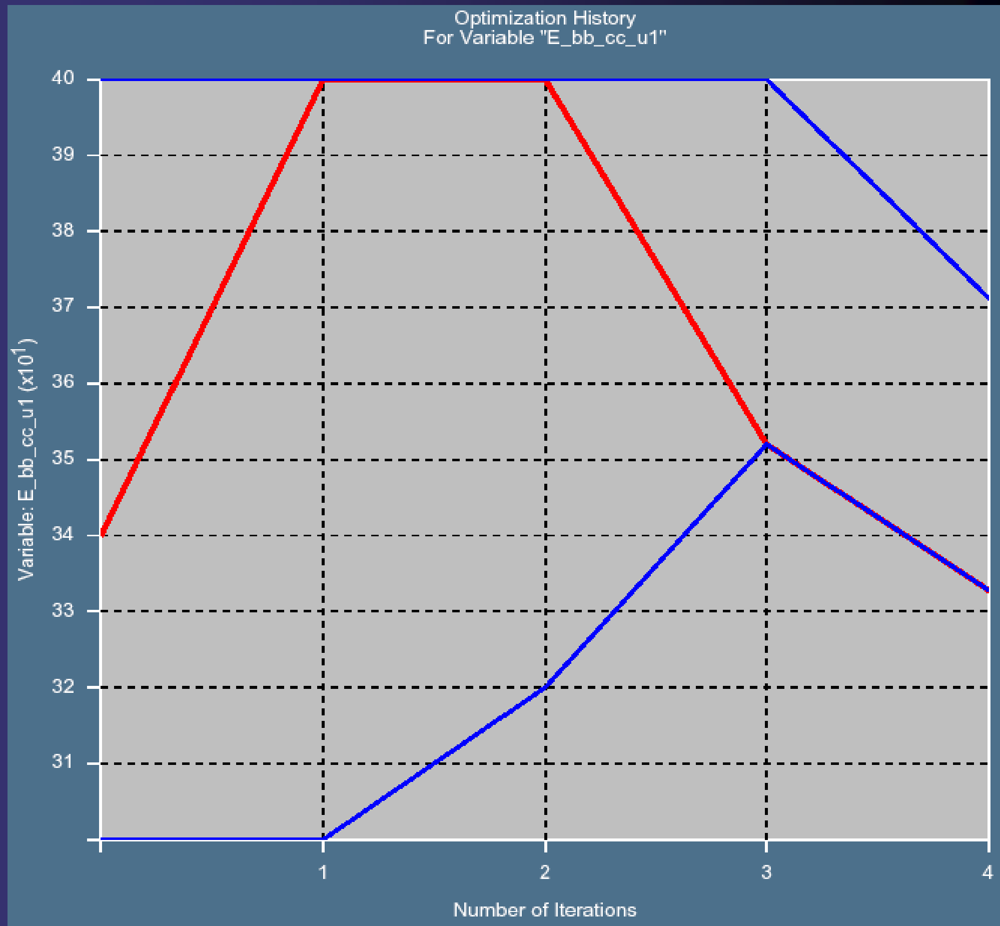
Yield Stress

COMPONENT BASED APPROACH

Results - Linear



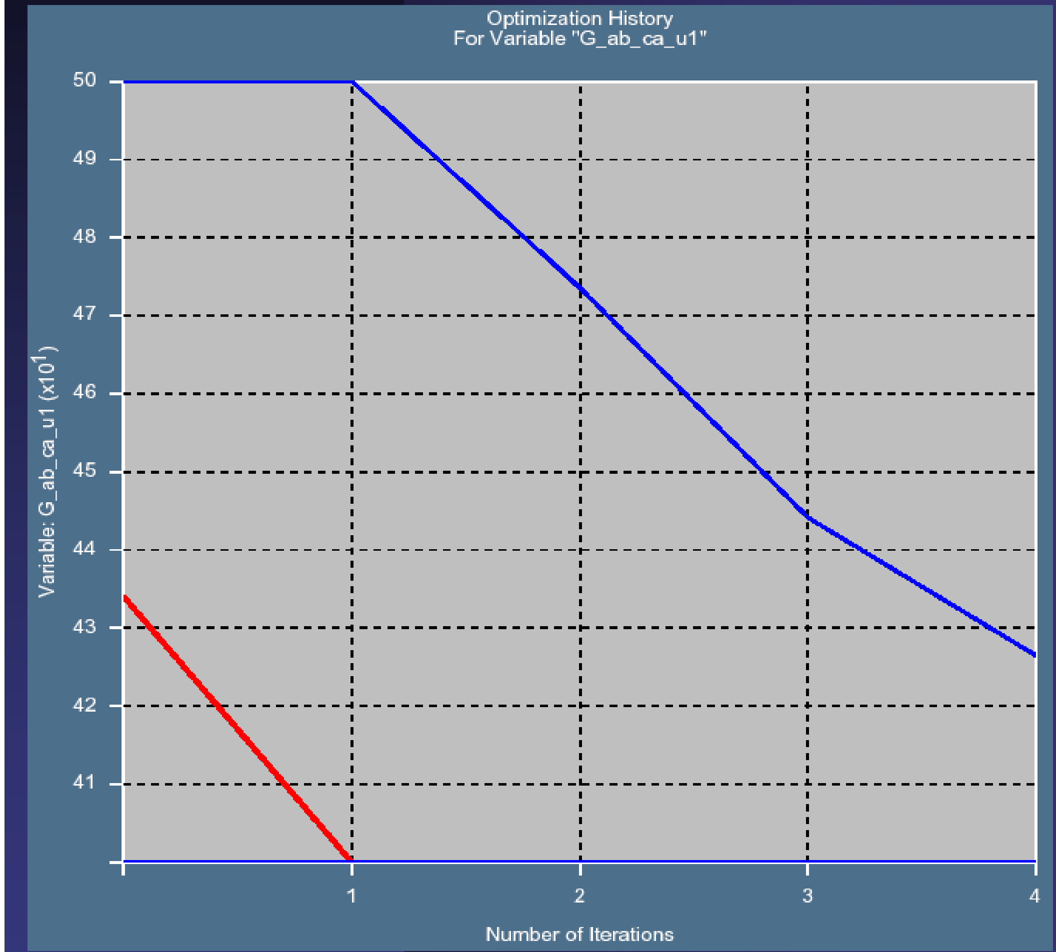
EAAU



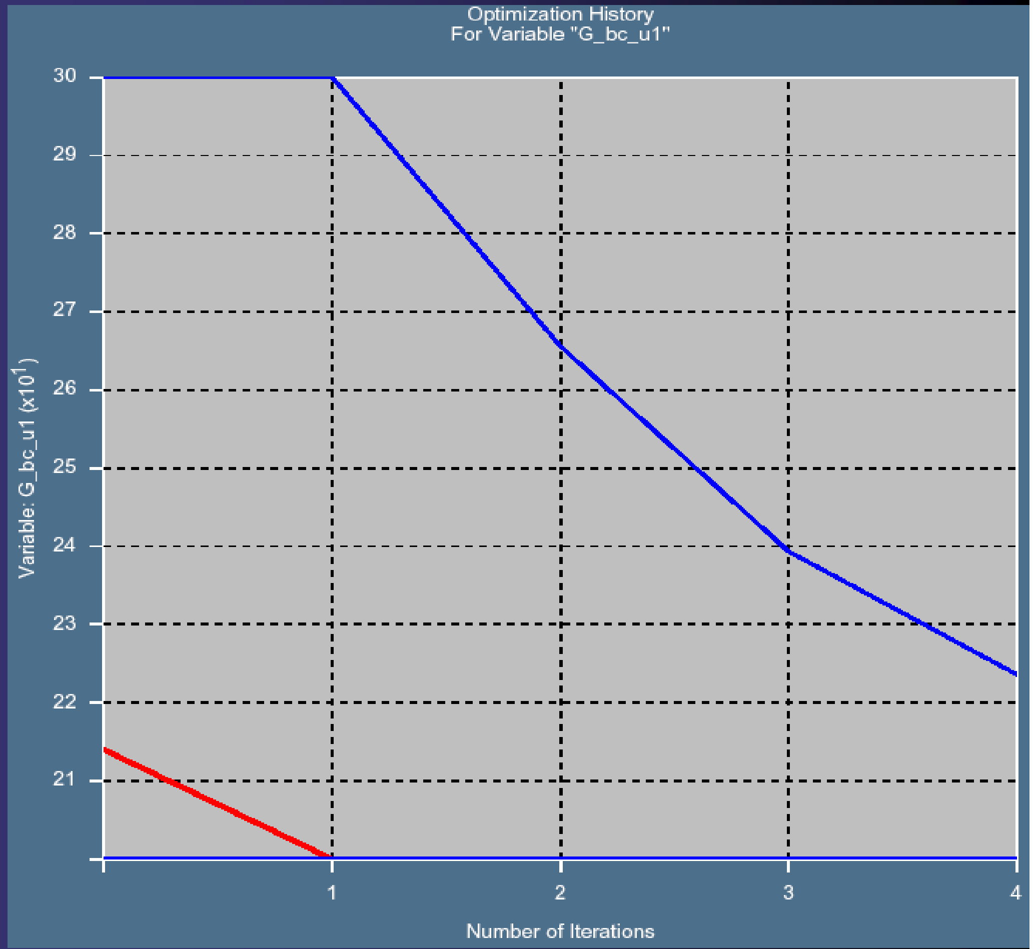
EBBU=ECCU

COMPONENT BASED APPROACH

Results - Linear



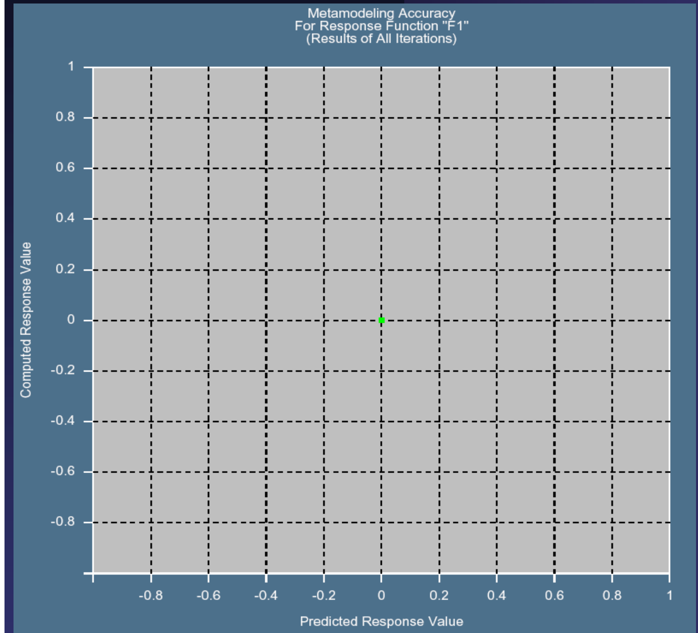
GABU=GCAU



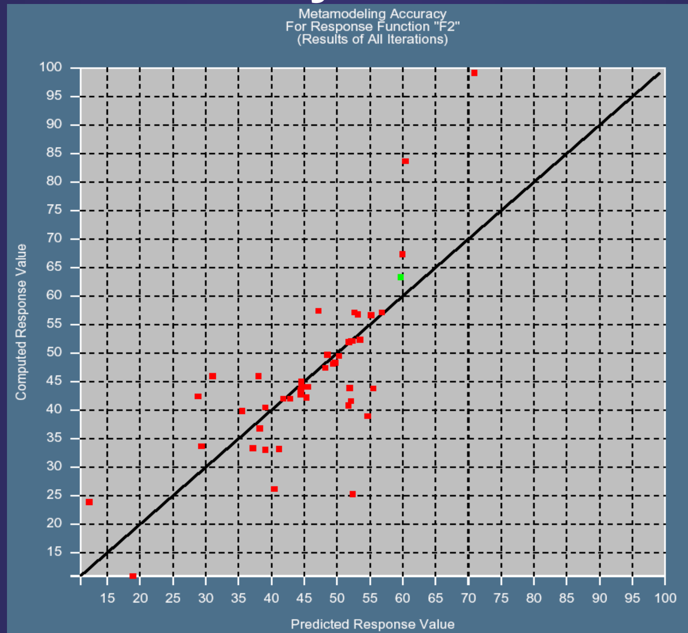
GBCU

COMPONENT BASED APPROACH

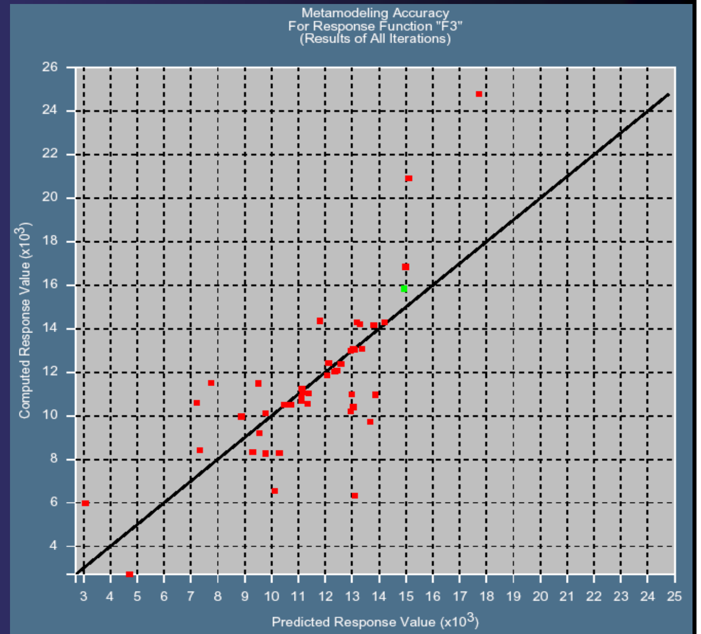
Accuracy - Linear



Force Response 1



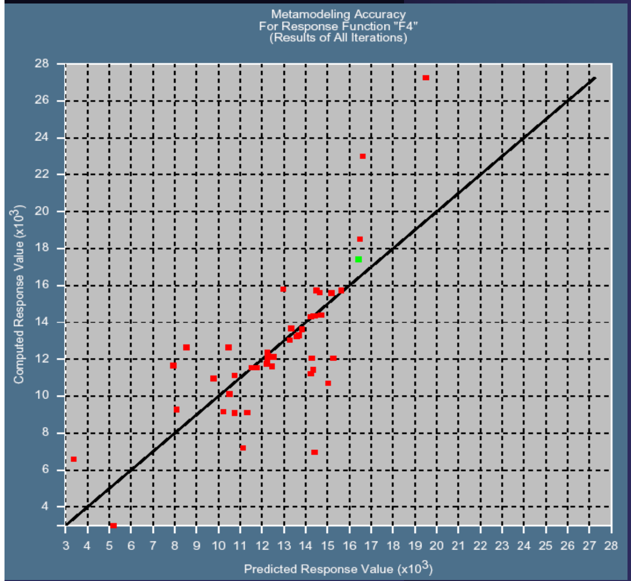
Force Response 2



Force Response 3

Optimum Should be close to the linear approximation where the design set is populated.

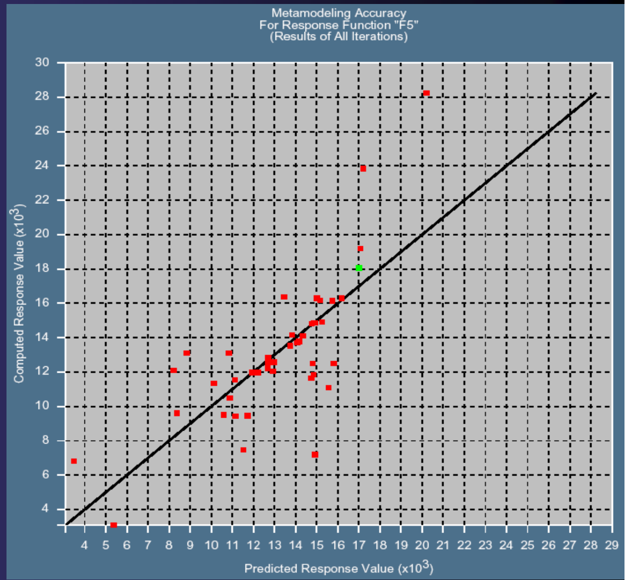
COMPONENT BASED APPROACH

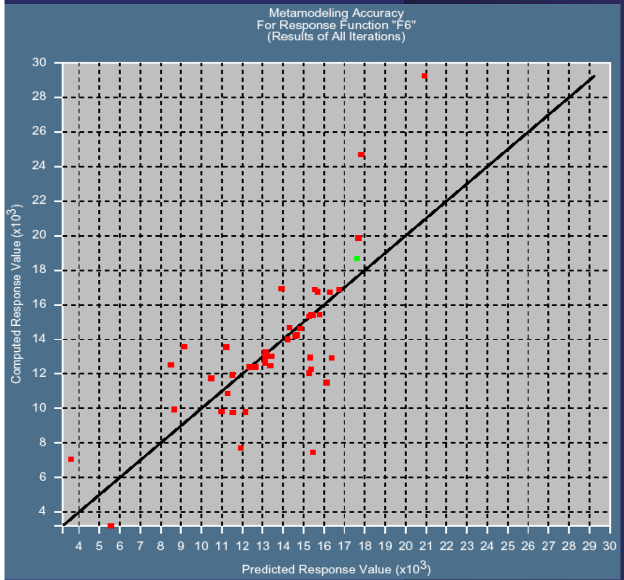


Accuracy - Linear

Force Response 4

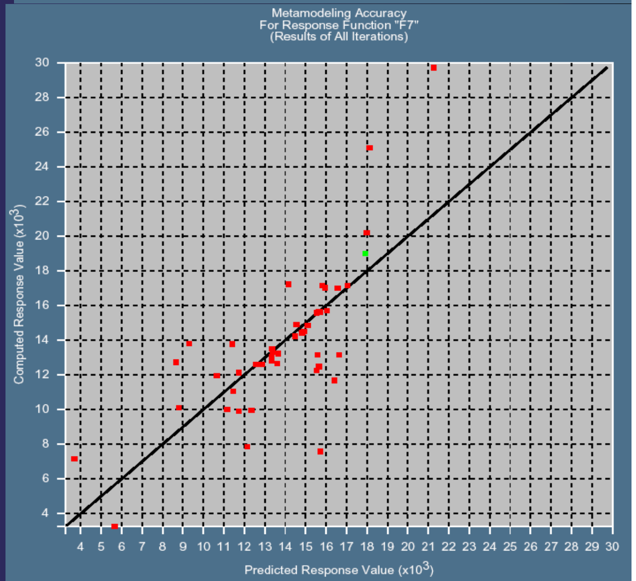
Force Response 5





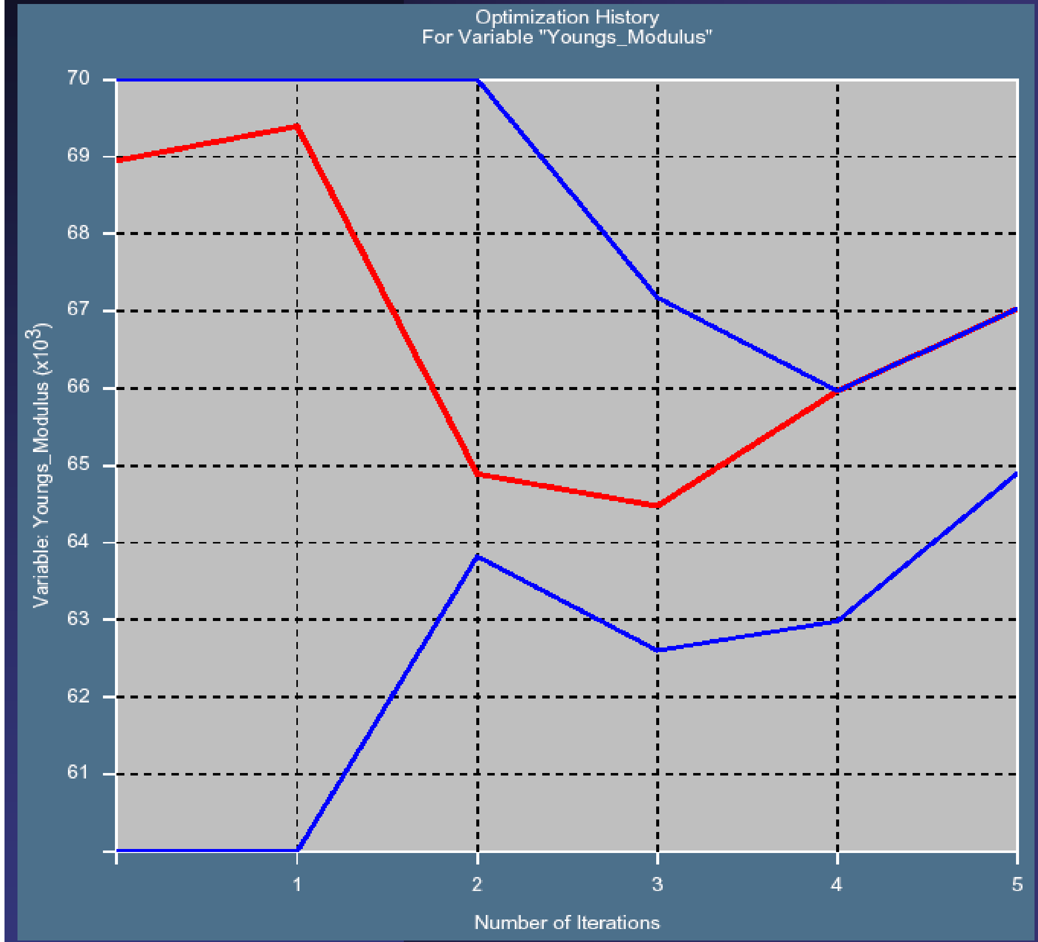
Force Response 6

Force Response 7

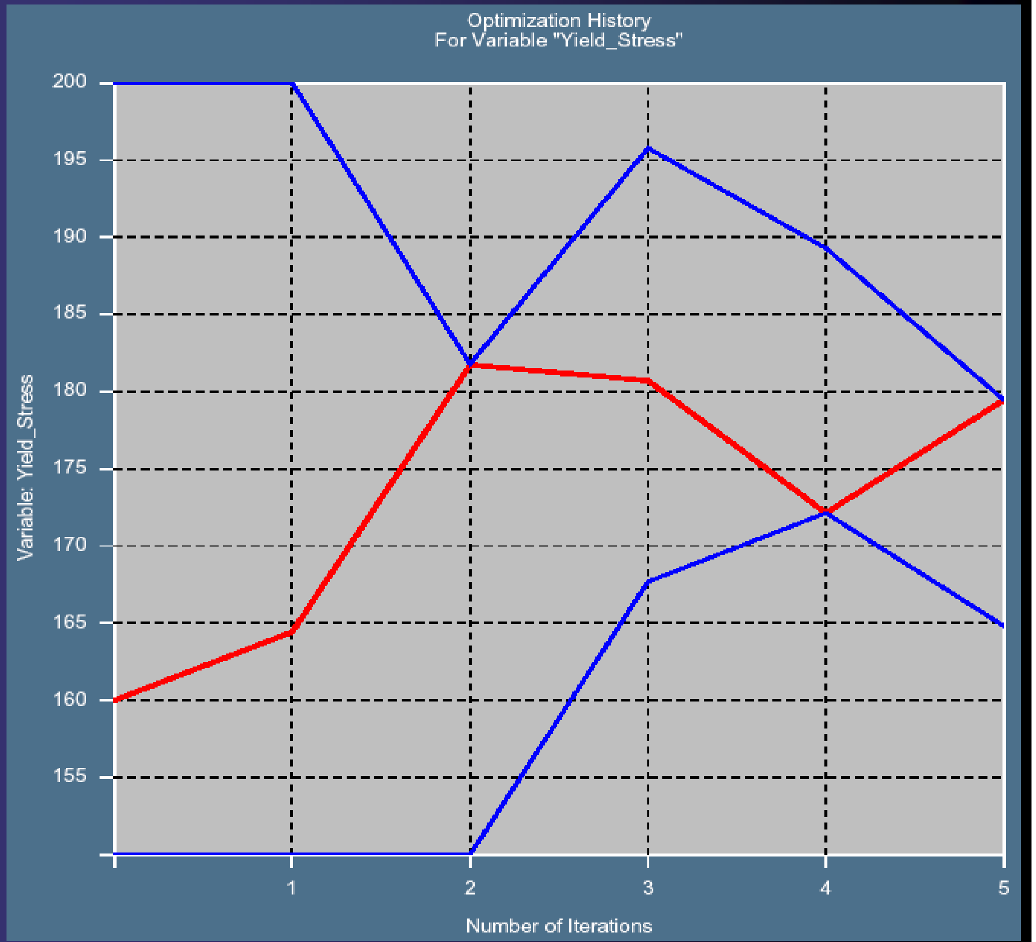


COMPONENT BASED APPROACH

Results - Quadratic



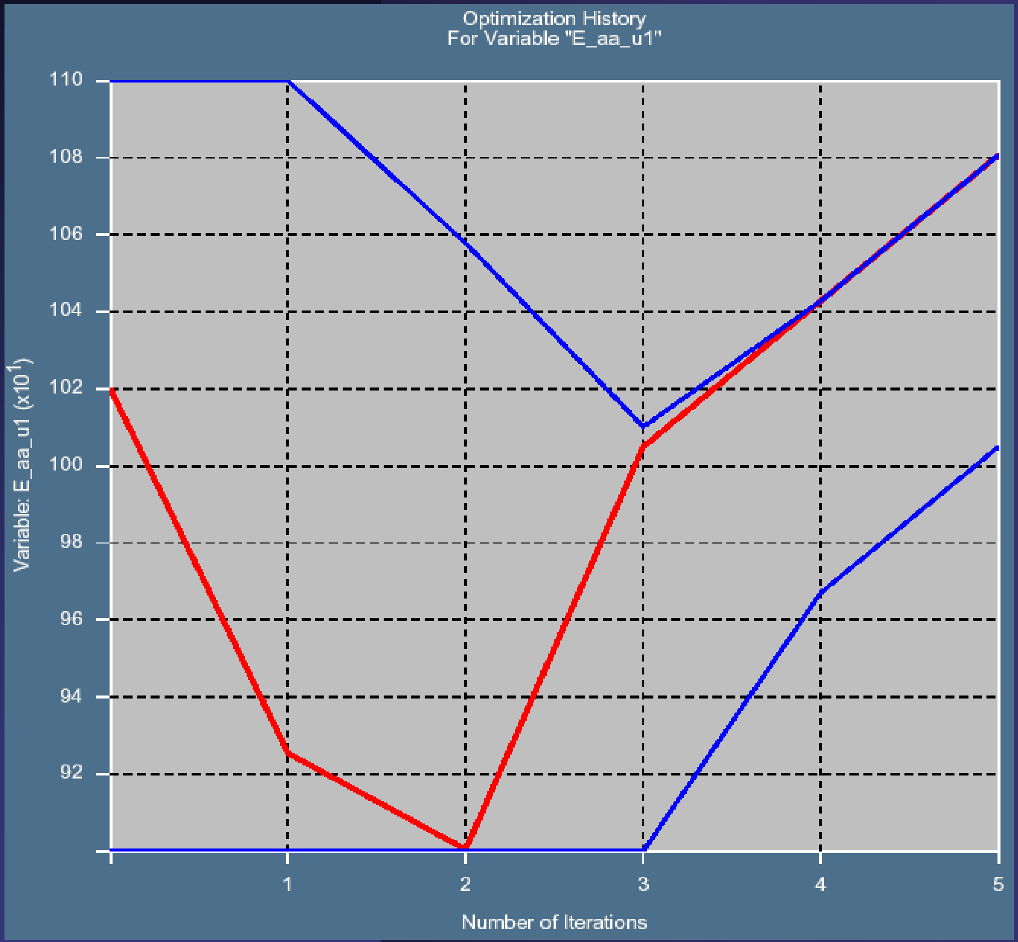
Young Modulus



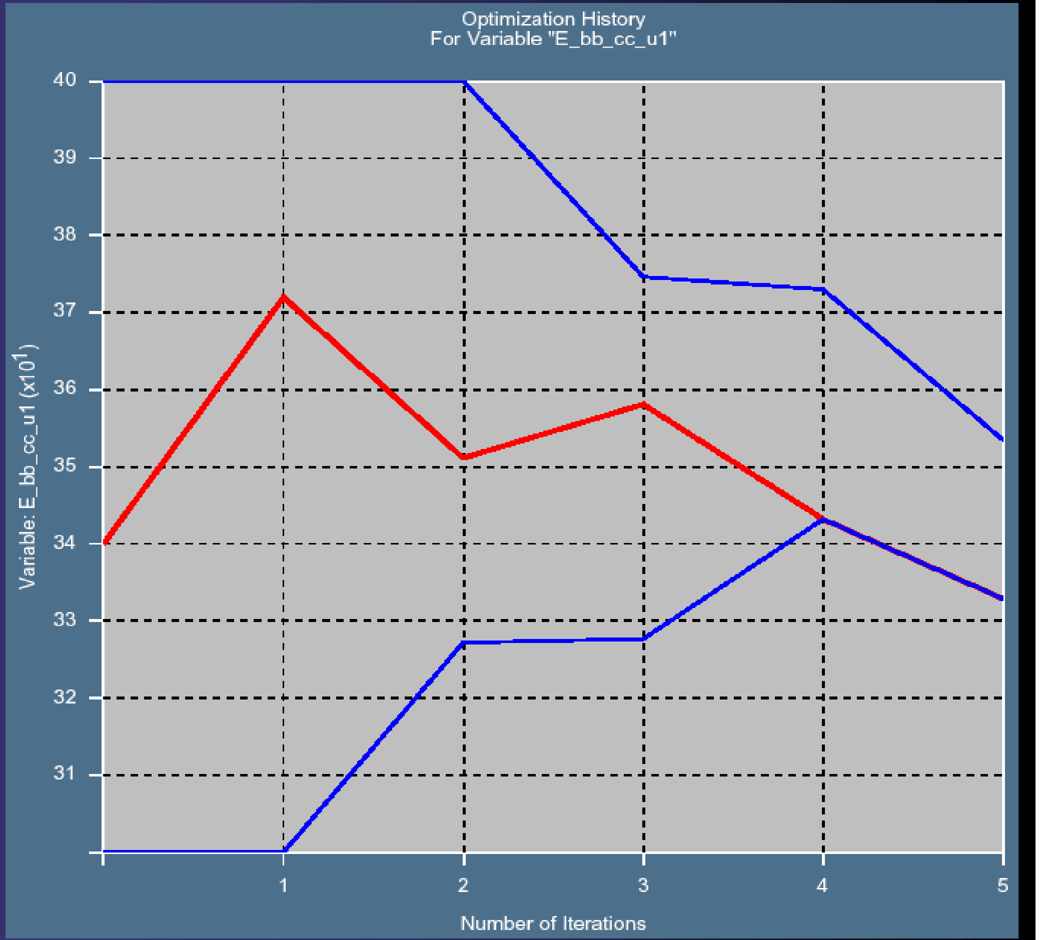
Yield Stress

COMPONENT BASED APPROACH

Results - Quadratic



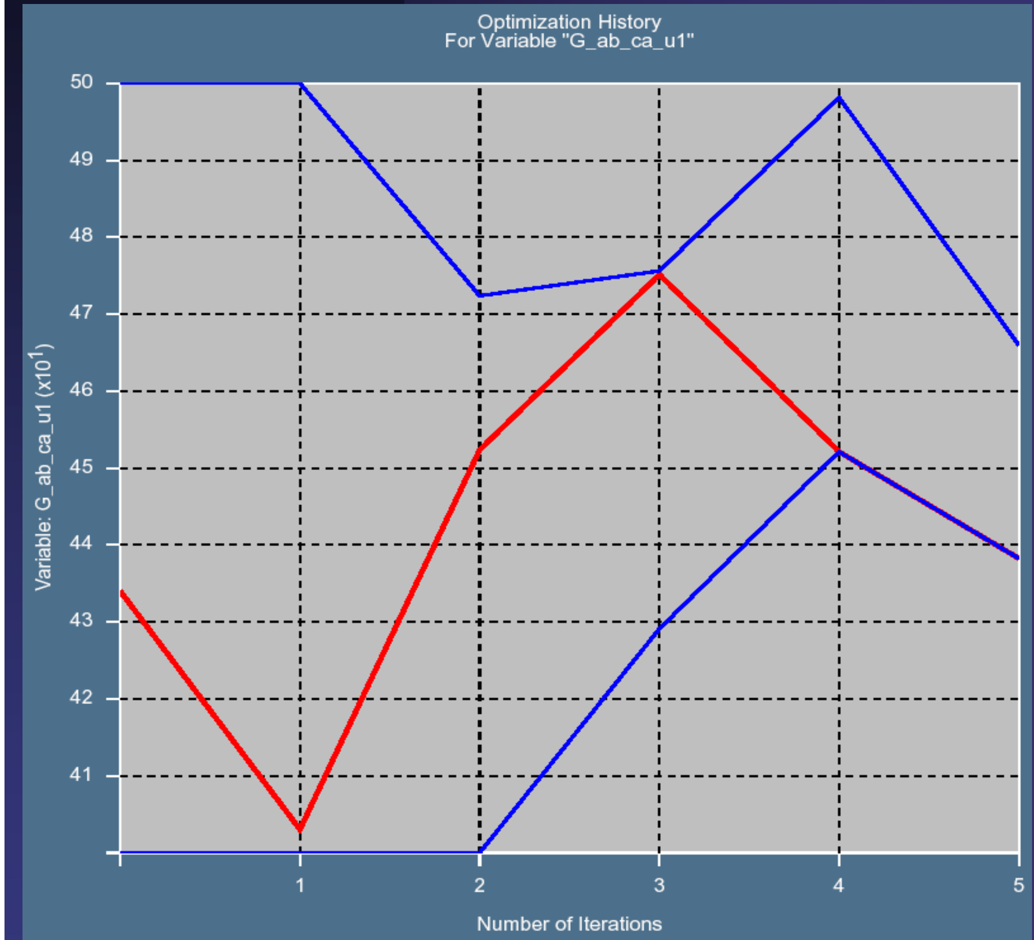
EAAU



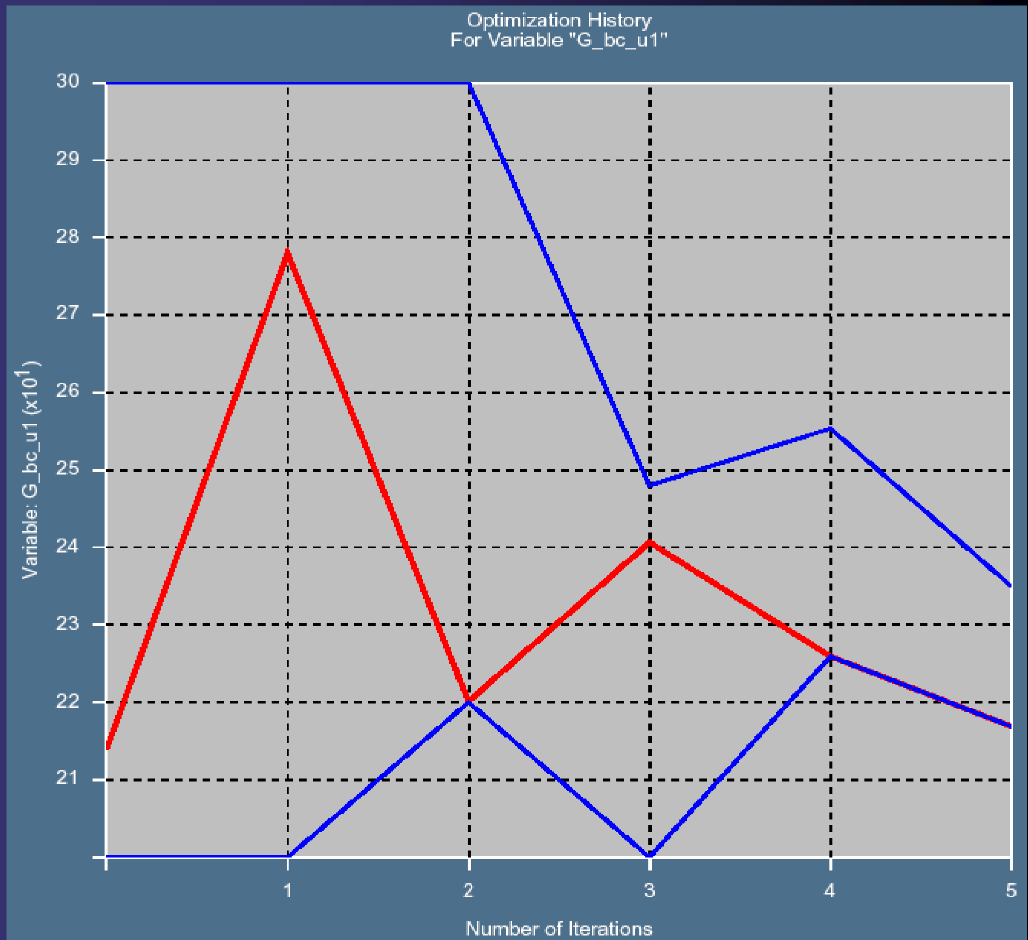
EBBU=ECCU

COMPONENT BASED APPROACH

Results - Quadratic



GABU=GCAU

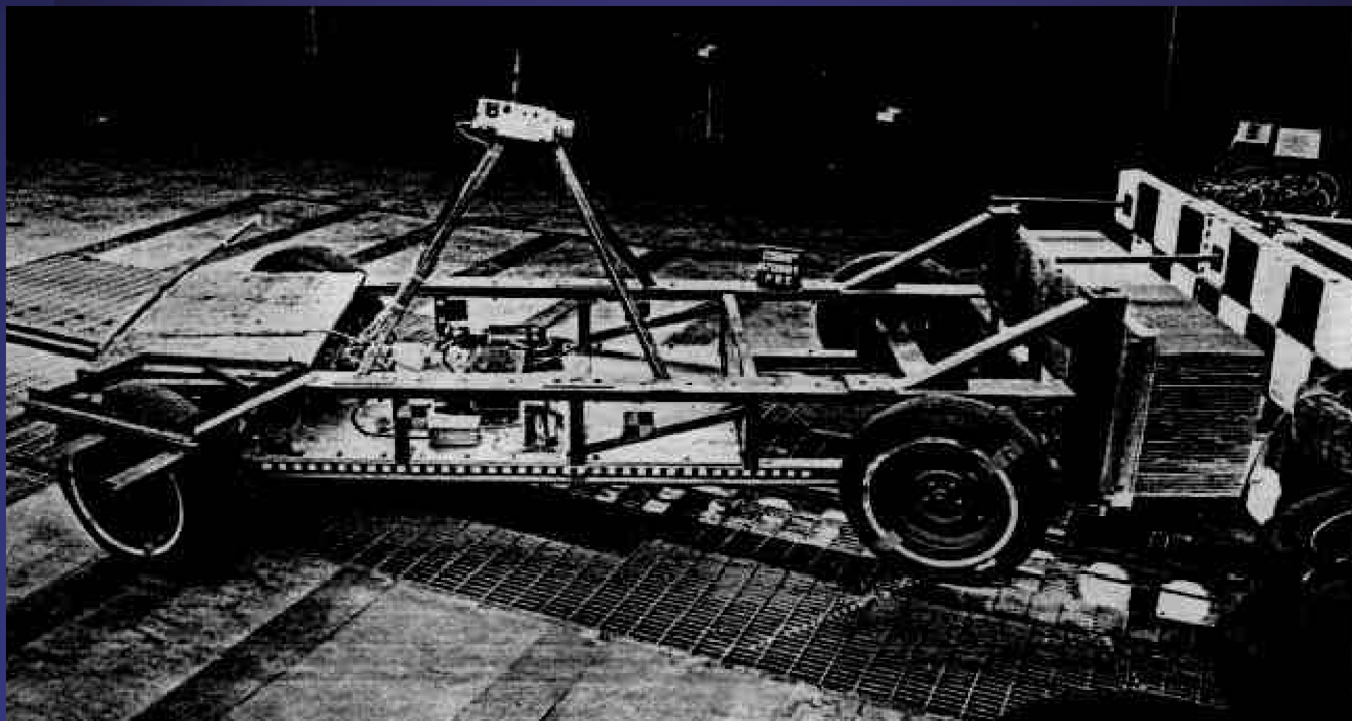


GBCU

FULL SCALE APPROACH

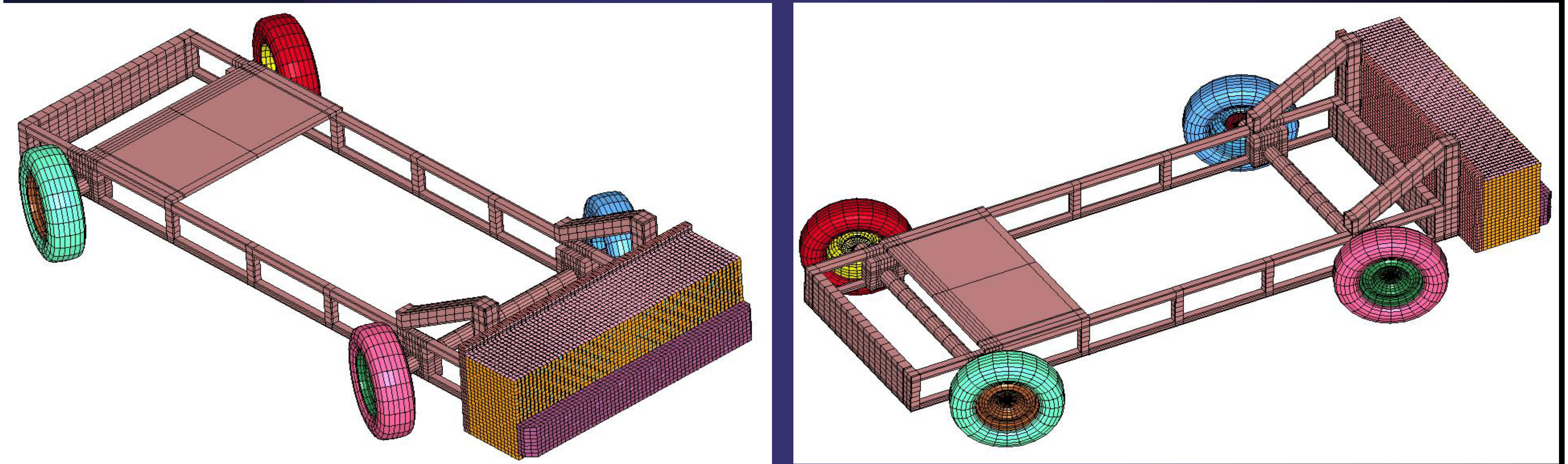
Test number V1068 conducted by NHTSA at the Vehicle Research and Test Center is used in this study.

In this test, the MDB was towed into a fixed load cell barrier at a perpendicular angle. The impact speed of the test was 40.2 km/h (25 mph), with the MDB crabbed at a 26^0 angle. The fixed load cell barrier was composed of 36 loads cells in a 4 rows x 9 columns configuration that is shown in the Figure.



FULL SCALE APPROACH

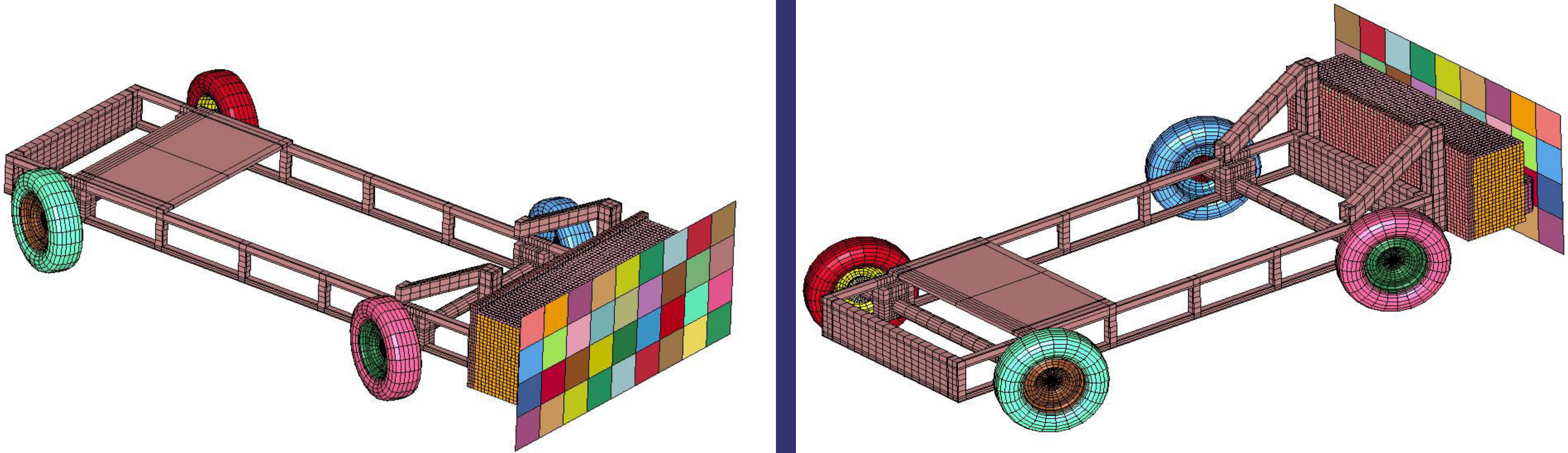
In this study, FE model of the FMVSS-214 MDB is used that is developed by FHWA/NHTSA National Crash Analysis Center (NCAC) based on an earlier version that was originally developed by NHTSA.



NCAC MDB finite element model

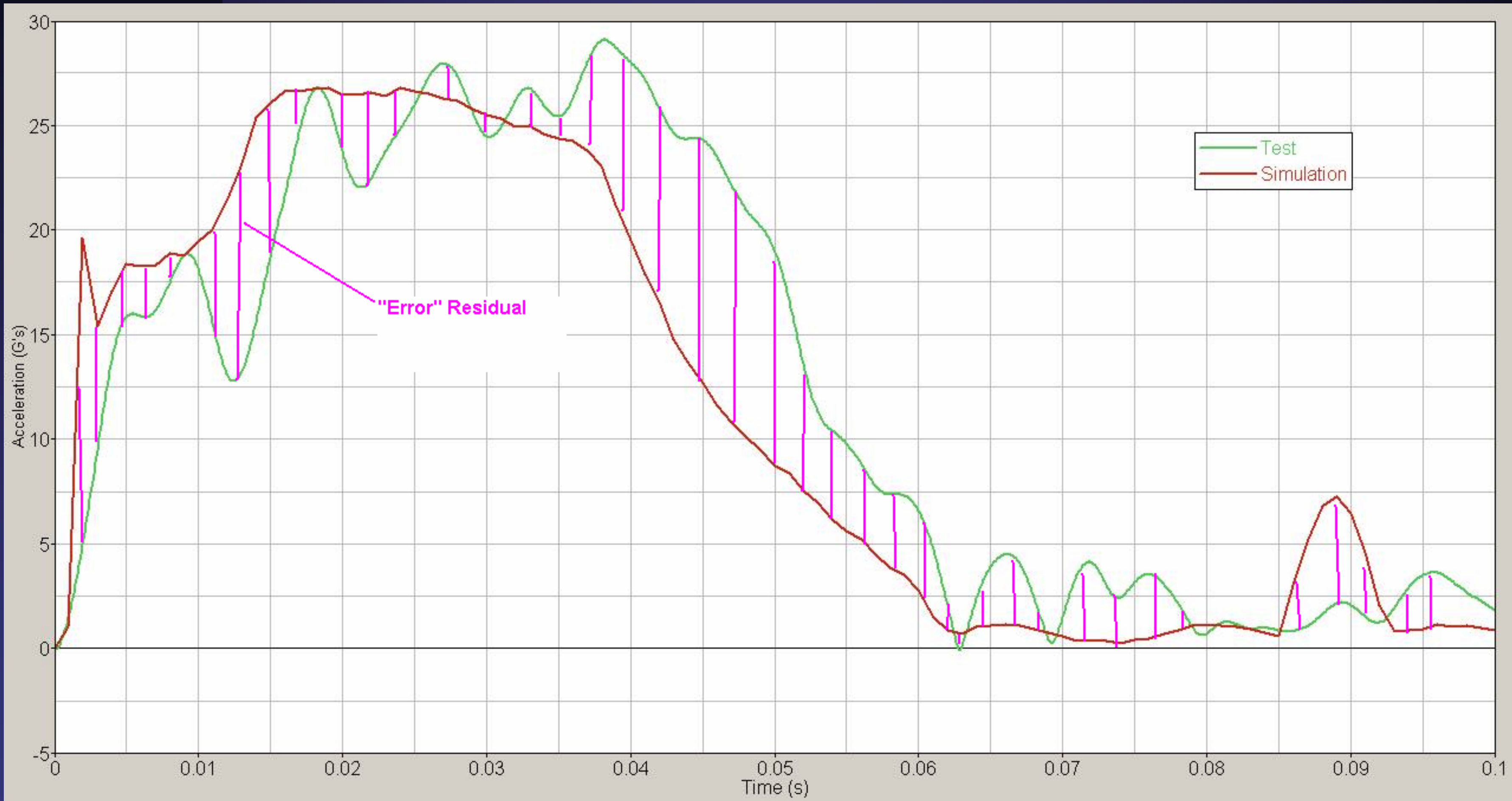
FULL SCALE APPROACH

In this study, a rigid wall impact scenario is considered to be able to compare the differences of the numerical models for a controlled environment which will be independent of the vehicle type.



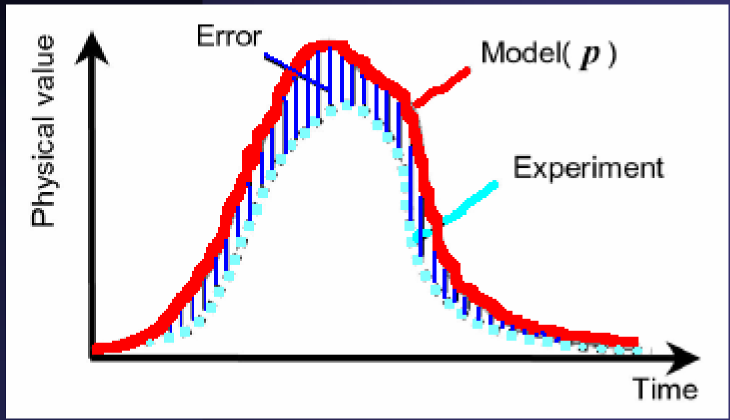
Test setup

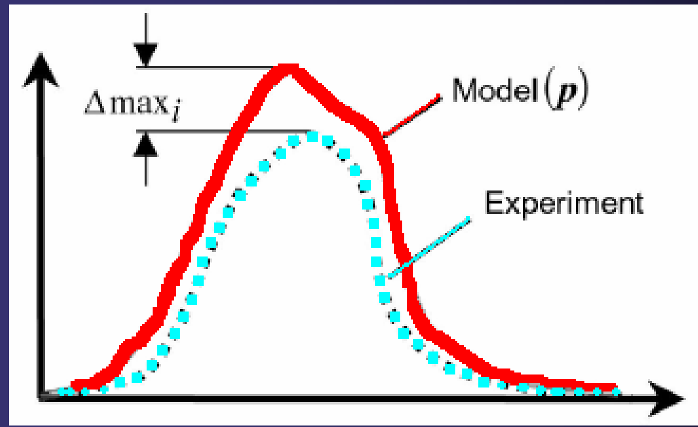
FULL SCALE APPROACH



The Objective Function to be Minimized "Residual"

FULL SCALE APPROACH





The Objective Function to be Minimized "Residual"

- **The acceleration measured through the crash test is selected as the baseline response function.**

- **The acceleration measured through the nodout ASCII output is selected as the simulation response function. (12 response points are selected)**

- **Minimizing the residual acceleration "Error" between the experimental and numerical data is the Objective.**

$$R(\boldsymbol{p}) = \left(\Delta\max_1(\boldsymbol{p})^2 + \cdots + \Delta\max_{12}(\boldsymbol{p})^2\right)^{1/2} \rightarrow \min.$$

FULL SCALE APPROACH

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	E	PR	SIGY	VF	MU	BULK
Type	I	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	.05	0.0

Card 2								
Variable	LCA	LCB	LCC	LCS	LCAB	LCBC	LCCA	LCSR
Type	F	F	F	F	F	F	F	F
Default	none	LCA	LCA	LCA	LCS	LCS	LCS	optional

Card 3	1	2	3	4	5	6	7	8
Variable	EAAU	EBBU	ECCU	GABU	GBCU	GCAU	AOPT	
Type	F	F	F	F	F	F		

Design Variables

Assumptions:

- **E and SIGY are accepted to be identical for TWO different honeycomb materials (45 psi and 245 psi)**
- **EBBU = ECCU and GAB = GCA**

So, There are 10 Independent Variables

CONCLUSION

❖LS-OPT was used successfully to determine constitutive model input parameters for a Mat_26-Honeycomb material.

❖A coupled component based compression and full scale crash test model is used for predicting the overall behavior better.

❖Linear vs. Quadratic approximation results are compared for RSM D-optimal algorithm for the component based study.

FUTURE WORK

- **Component based tension and shear tests are also going to be coupled.**

- **Stress vs. volumetric strain curves are also going to be integrated in the optimization algorithm as variables.**

- **For more than 10 independent variables, especially for a full scale model, MPP would be mandatory.**