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Agile Modeling of Component Connections for Simulation and Design of Complex Vehicle Structures

Matthew P. Castanier, David A. Lamb, and David J. Gorsich
U.S. Army
Tank Automotive Research, Development, and Engineering Center (TARDEC)
Warren, MI

Keychun Park
University of Michigan
Department of Mechanical Engineering
Ann Arbor, MI

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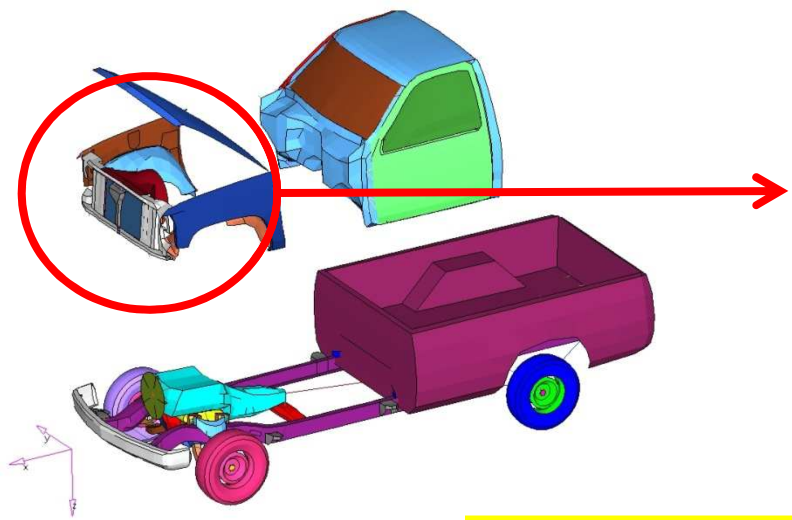
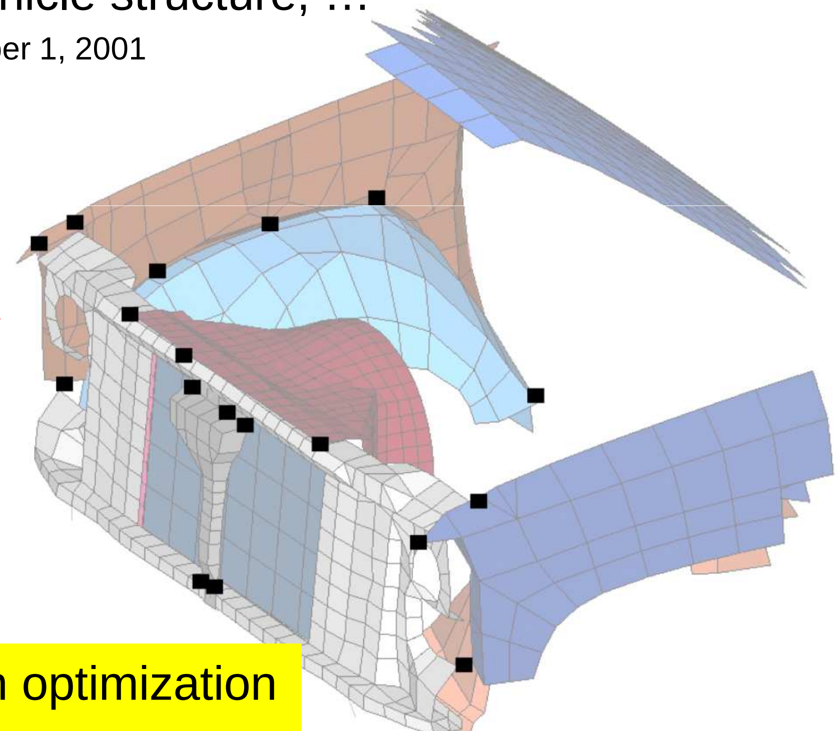
Overview

- Background and Motivation
- Methods for joining topology optimization
- Numerical Results
- Conclusions

Motivation

- How to Join the components ?
  - "… 4,608 spot welds on the [vehicle], which had just 1.4 m of laser welding… "
    By Dr. Klaus Loeffler, Director, Joining Processes, Volkswagen AG,
    -- Automotive Design and Production, May 4, 2007
  - "… more than 4,000 spot welds connect some 300 body panels on a typical mid-sized car to form the basic vehicle structure, …"
    By Louise Elliott, Regional Editor -- Design News, October 1, 2001

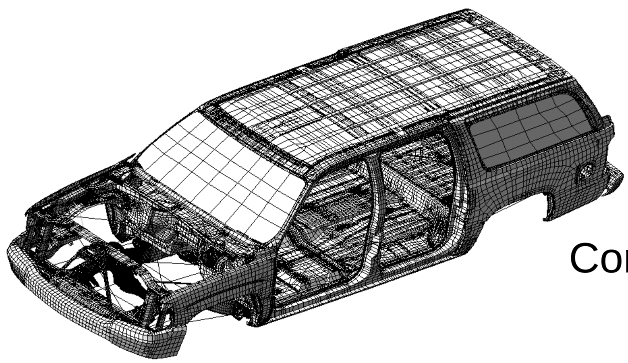




Hard to determine joining locations

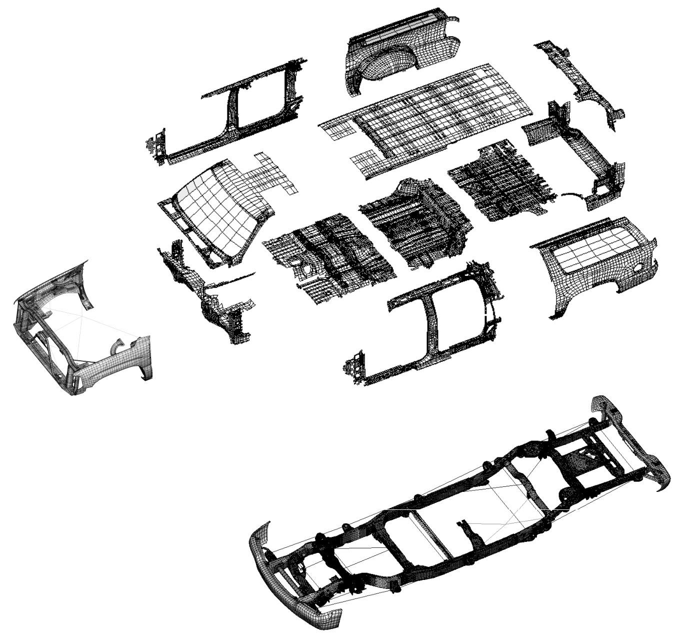
Joining design optimization Among components

Reduced order modeling



Divide and Conquer

Component Mode Synthesis (CMS)

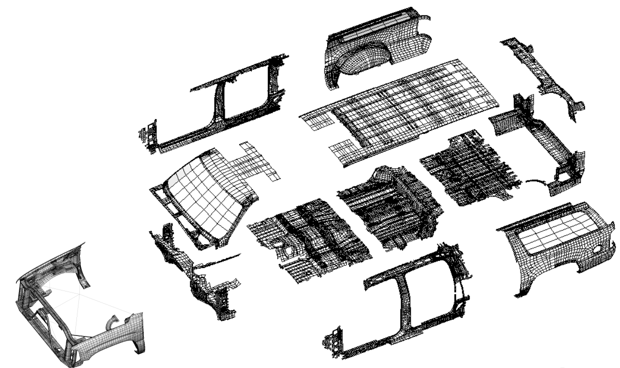


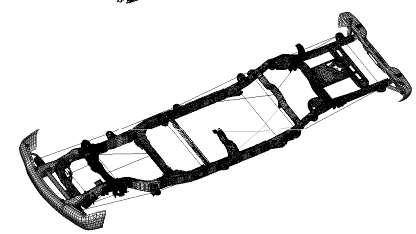
- Divide structure into substructures (components)

- Use component mode synthesis (CMS) to generate reduced-order models (ROMs)
  1. ROM size << FEM size due to modal analysis for each component
  2. **ROM retains physical (FE) DOF at interface between components**

Joining modeling & design approach

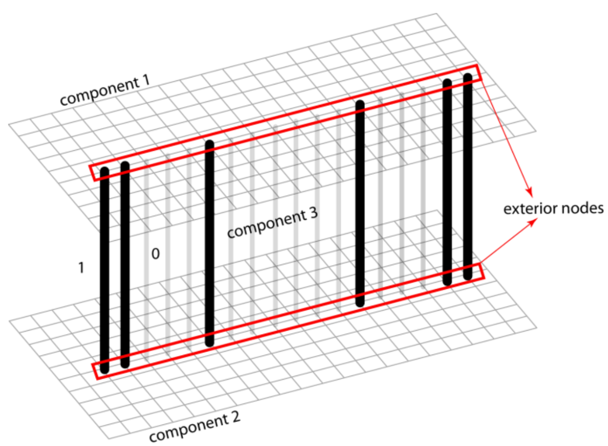
- Divide structure into components such that interface between components includes potential joining locations
  - **ROM retains physical (FE) DOF for potential joining locations**





- Treat connections between two components as joining design variables (joining is treated like a "third component")
  - Continuous variable: e.g., spring with varying stiffness
  - Discrete variable: connection is on or off

- Perform joining design optimization to achieve system-level performance requirements



Previous joining design research

- System level topology optimization in full order model :
  Extension of the component topology optimization (Bensøe and Kikuchi , (1988))

  - Chirehdast and Jian (1996)
    - Optimal design of spot-weld and adhesive bond patterns for static compliance
  - Chickermane and Gea (1997)
    - Multi-component structural systems for optimal layout topology and joint locations for static compliance

- Interface design via ROM
  - Jiang , Cui, Ma, and Hadi (2005)
    - Optimal mount position and mount properties via size optimization

- Objectives of this work:

⇨

1. Use ROM to perform fast system-level analysis and joining design optimization
2. Optimize joining for static and dynamic structural response objectives while constraining maximum joining area

Structural Topology Optimization

Design Domain Modeling

- **Homogenization Method** – Bensøe and Kikuchi
  - ✓ Relatively stable, but slow
- **SIMP** (Solid Isotropic Material with Penalization) – Bensøe and Sigmund
  - ✓ Relatively fast, small number of design variables

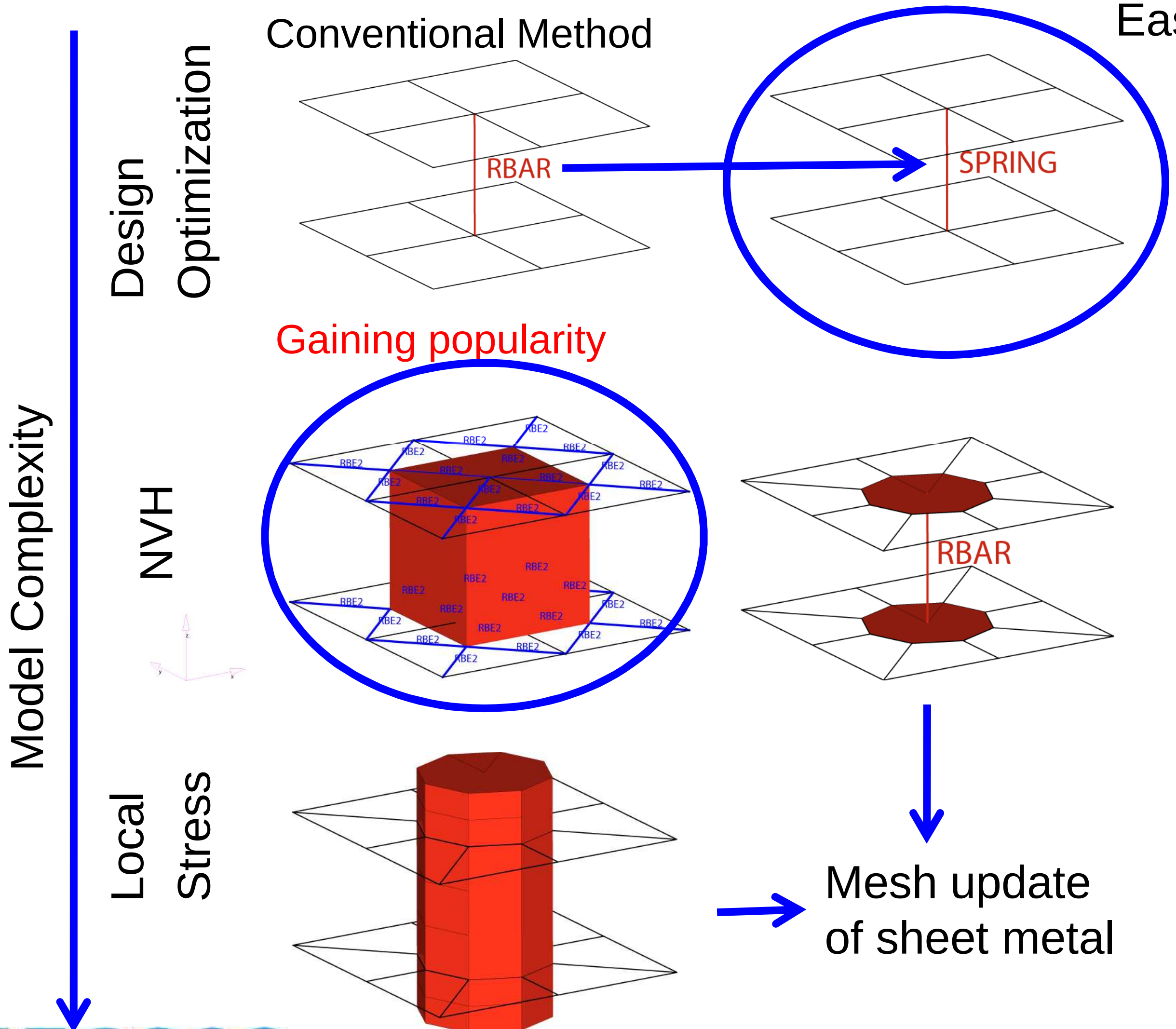
Optimization Methods

- **OC (Optimality Criteria)** – Karush, Khun and Tucker
  - ✓ KKT Condition and Nonlinear Solver
- **MOC (Modified OC)** – Ma, Kikuchi, and Hagiwara ('93)
  - ✓ Shifted Lagrangian in OC
- **MMA (Method of Moving Asymptotes)** – K. Svanberg ('87)
  - ✓ Convex Linearization with Asymptotes of Objective and Constraints

Joining modeling in FEA

- Dominant Joining (Spot-Welding) modeling

Ease of automatic updating

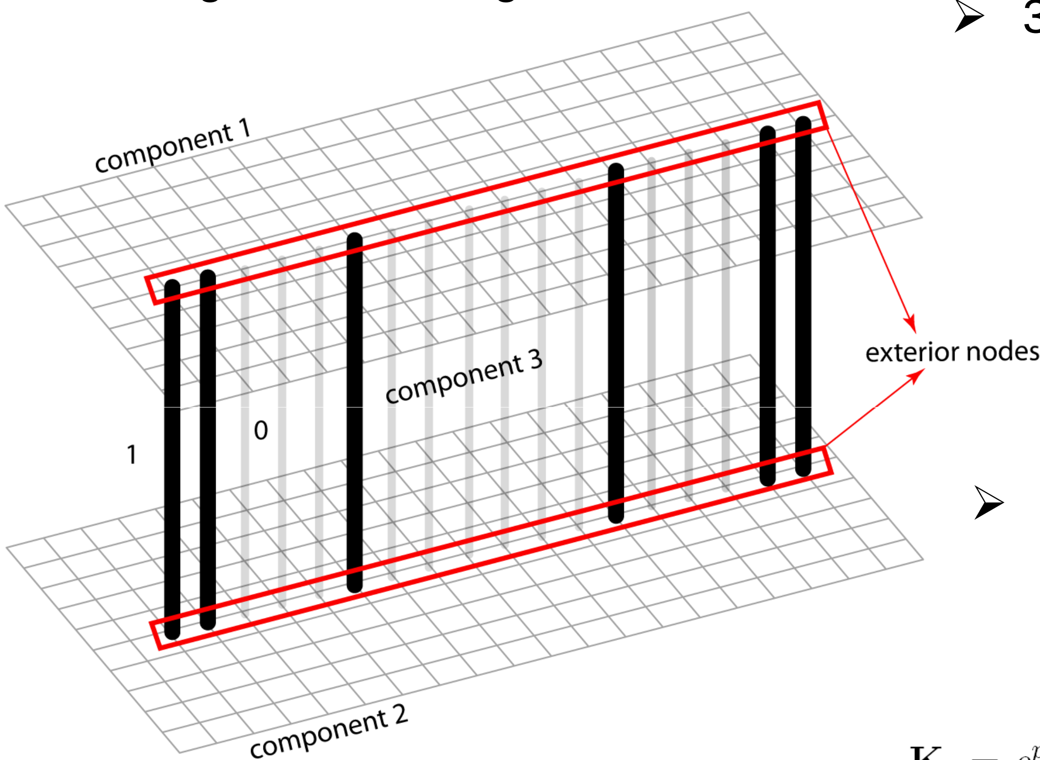


$$\mathrm{K_s} = \begin{bmatrix} \mathrm{k_s} & -\mathrm{k_s} \\ -\mathrm{k_s} & \mathrm{k_s} \end{bmatrix}$$

$$\mathrm{k_s} = \mathrm{k_y}\,\mathrm{Diag}([\mu_k \; 1 \; \mu_k])$$

Joining modeling in current study

- Topology optimization for joining (Design domain modeling + Optimizer) in ROM
  Leading to "0-1" design



➢ 3D Spring with continuous variables

$$\mathbf{K_s} = \begin{bmatrix} \mathbf{k_s} & -\mathbf{k_s} \\ -\mathbf{k_s} & \mathbf{k_s} \end{bmatrix}$$

$$\mathbf{k_s} = \mathbf{k_y}\,\mathbf{Diag}([\alpha_\mathbf{k}\ \mathbf{1}\ \alpha_\mathbf{k}])$$

➢ Design domain modeling
   ✓ SIMP (Solid Isotropic Material with Penalization)

$$\mathbf{K}_e = \rho_e^p \begin{bmatrix} \mathbf{k}_s & -\mathbf{k}_s \\ -\mathbf{k}_s & \mathbf{k}_s \end{bmatrix} = \rho_e^p \mathbf{K}_s^0 \qquad \sum_{e=1}^{n_{var}} \rho_e = V \leq N$$

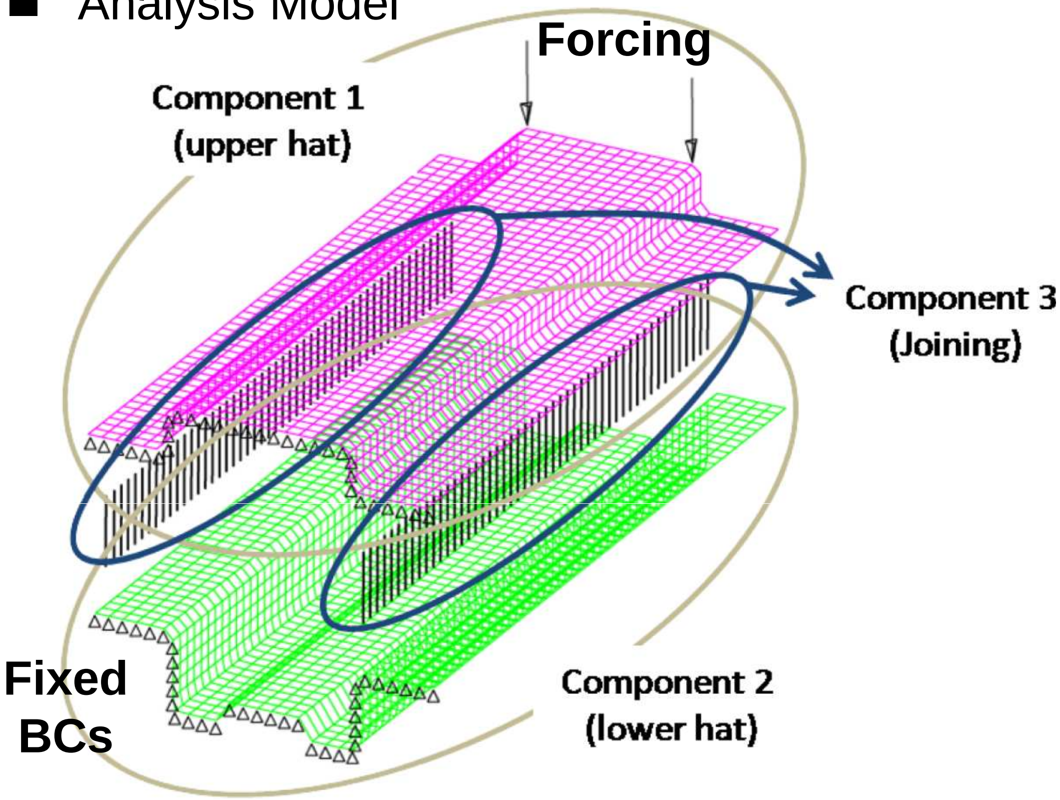
➢ Topology Optimizer

✓ MMA (Method of Moving Asymptote) – K. Svanberg ('87)

✓ MOC (Modified OC) – Z.-D. Ma, N. Kikuchi, I.Hagiwara ('93)
Applicability both dynamic and static problems

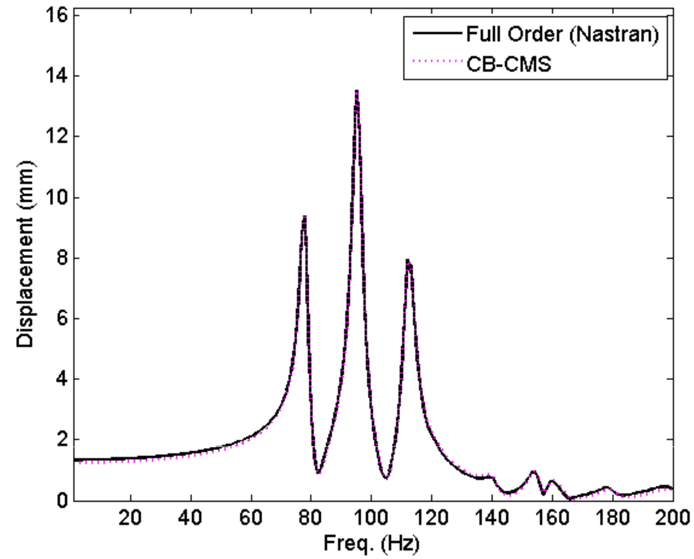
Structure used for numerical results

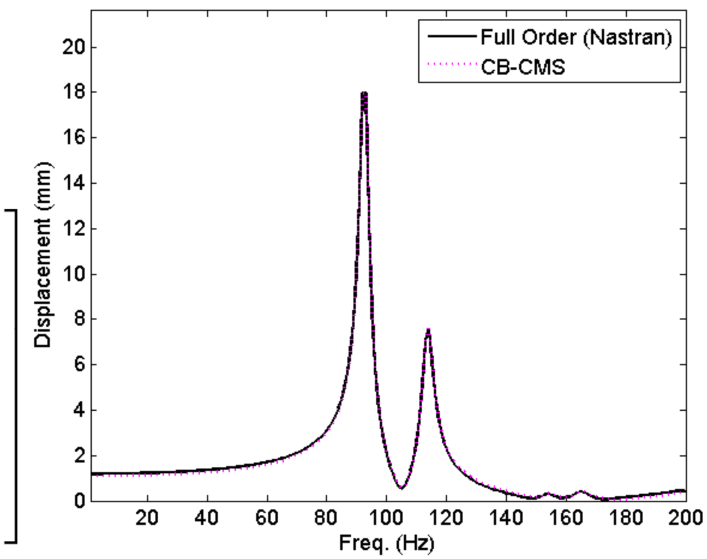
- Analysis Model



$$\begin{bmatrix} \mathbf{m}_u^{C} & 0 & \mathbf{m}_u^{CN} & 0 \\ 0 & \mathbf{m}_l^{C} & 0 & \mathbf{m}_l^{CN} \\ \mathbf{m}_u^{NC} & 0 & \mathbf{m}_u^{N} & 0 \\ 0 & \mathbf{m}_l^{NC} & 0 & \mathbf{m}_l^{N} \end{bmatrix} \quad \begin{bmatrix} \mathbf{k}_u^{C} + \mathbf{k}_s^{u} & \mathbf{k}_s^{ul} & \mathbf{k}_l^{CN} & 0 \\ \mathbf{k}_s^{lu} & \mathbf{k}_l^{C} + \mathbf{k}_s^{l} & 0 & \mathbf{k}_u^{CN} \\ \mathbf{k}_u^{NC} & 0 & \mathbf{k}_u^{N} & 0 \\ 0 & \mathbf{k}_l^{NC} & 0 & \mathbf{k}_l^{N} \end{bmatrix}$$

- ROM Validation





Optimization: static case

- Joining topology optimization for minimizing static compliance

$$\min_{\boldsymbol{\rho}} \quad c(\boldsymbol{\rho}) = \sum_{load=1}^{l_n} \mathbf{f}^{\mathbf{T}}\mathbf{U} = \sum_{\mathbf{load=1}}^{\mathbf{l_n}} \mathbf{U}^{\mathbf{T}}\mathbf{K_{st}}\mathbf{U}$$

$$s.t.: \quad g(\boldsymbol{\rho}) = \sum_{e=1}^{n_{var}} \rho_e - N \leq 0\,; \quad 0 < \rho_{min} \leq \rho_e \leq 1$$

$$\mathbf{K}_{st} = \mathbf{K}^0 + \mathop{\mathbf{A}}_{e=1}^{n_{var}} \rho_e^p \begin{bmatrix} \mathbf{k_s} & -\mathbf{k_s} \\ -\mathbf{k_s} & \mathbf{k_s} \end{bmatrix}$$

  - Fast evaluation via reduced order modeling for $\mathbf{K_{st}}\mathbf{U} = \mathbf{f}$

- **OC method (Bensøe and Kikuchi ,1988)**

Define Lagrangian → Stationary condition ← Design sensitivity

$$\mathcal{L} = c(\boldsymbol{\rho}) + \Lambda g(\boldsymbol{\rho})$$

$$B_K = -\Lambda_K^{-1} \frac{\partial c / \partial \rho_e}{\partial g / \partial \rho_e}$$

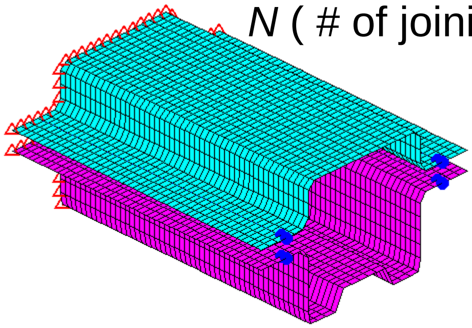
$$\frac{\partial c(\boldsymbol{\rho})}{\partial \rho_e} = -p{\rho_e}^{p-1}\mathbf{u}_e^{\mathrm{T}}\mathbf{K}_s^0\mathbf{u}_e$$

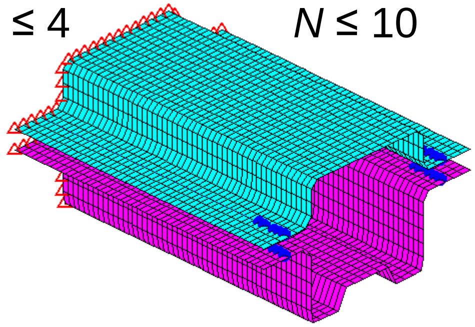
Update Rule

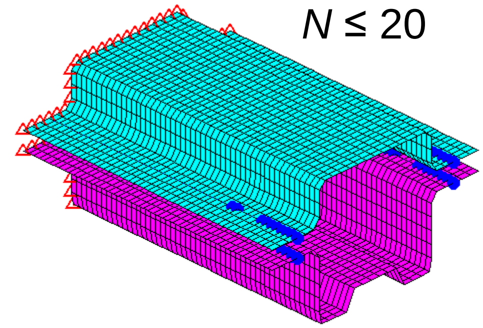
$$\rho_{K+1} = \begin{cases} \max\{(1-\zeta)\rho_K, \rho_{min}\} & \text{if} \quad \rho_K B_K^\eta \leq \max\{(1-\zeta)\rho_K, \rho_{min}\}, \\ \min\{(1+\zeta)\rho_K, 1\} & \text{if} \quad \min\{(1+\zeta)\rho_K, 1\} \leq \rho_K B_K^\eta, \\ \rho_K B_K^\eta & \text{otherwise.} \end{cases}$$

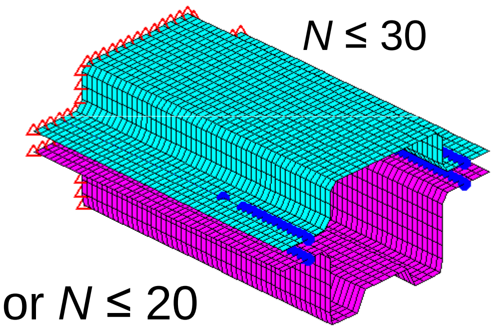
Optimization results: static case

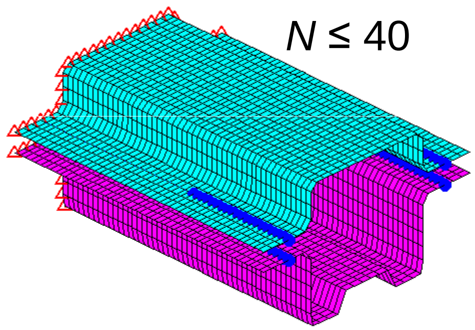
- Resulting Joining Topology

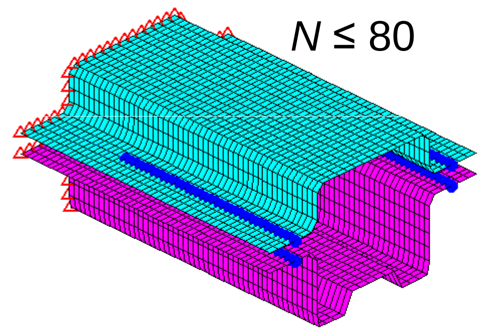




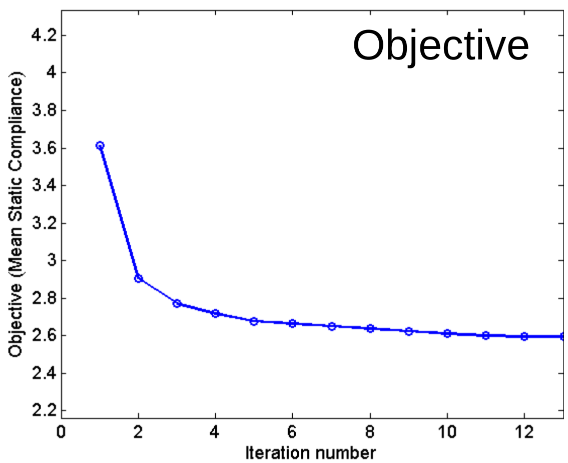


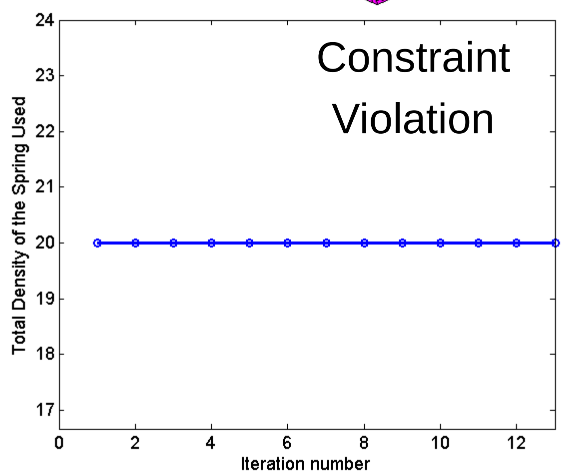


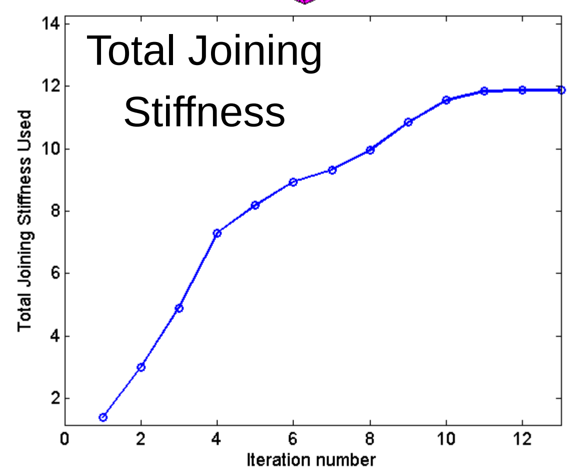




- For *N* ≤ 20







Optimization: dynamic case

- Joining topology optimization for minimizing dynamic compliance

$$\min_{\rho} \int_{f_{low}}^{f_{high}} \sum_{load=1}^{l_n} |\mathbf{f^T U}(\rho)|\mathbf{df} \qquad \mathbf{K}_{st} = \mathbf{K}^0 + \mathop{\mathbf{A}}_{e=1}^{n_{var}} \rho_e^p \begin{bmatrix} \mathbf{k_s} & -\mathbf{k_s} \\ -\mathbf{k_s} & \mathbf{k_s} \end{bmatrix}$$

$$s.t.: \quad g(\boldsymbol{\rho}) = \sum_{e=1}^{n_{var}} \rho_e - N \le 0\,; \quad 0 < \rho_{min} \le \rho_e \le 1$$

  - Fast evaluation via reduced order modeling for $\mathbf{M\ddot{U}} + \mathbf{KU} = \mathbf{f_{ext}}$

- **Modified OC method (Ma, *et al*.,1992)**

Define Lagrangian → Stationary condition ← Design sensitivity

$$\mathcal{L} = (c(\boldsymbol{\rho}) - \mu g(\boldsymbol{\rho})) + (\Lambda + \mu) g(\boldsymbol{\rho}) = \tilde{c} + \tilde{\Lambda} g(\boldsymbol{\rho})$$

$$B_{K,MOC} = \tilde{\Lambda}_K^{-1} \left[\mu_K - \left(\frac{\partial c/\partial \rho_e}{\partial g/\partial \rho_e} \right) \right]$$

$$\mu > \max_{e=1,n_{var}} \frac{\partial c/\partial \rho_e}{\partial g/\partial \rho_e}$$

$$\frac{\partial c(\boldsymbol{\rho})}{\partial \rho_e} = -sgn(\mathbf{f}^T\mathbf{U}) p \rho_e^{p-1} \mathbf{u}_e^T \mathbf{K}_s^0 \mathbf{u}_e$$

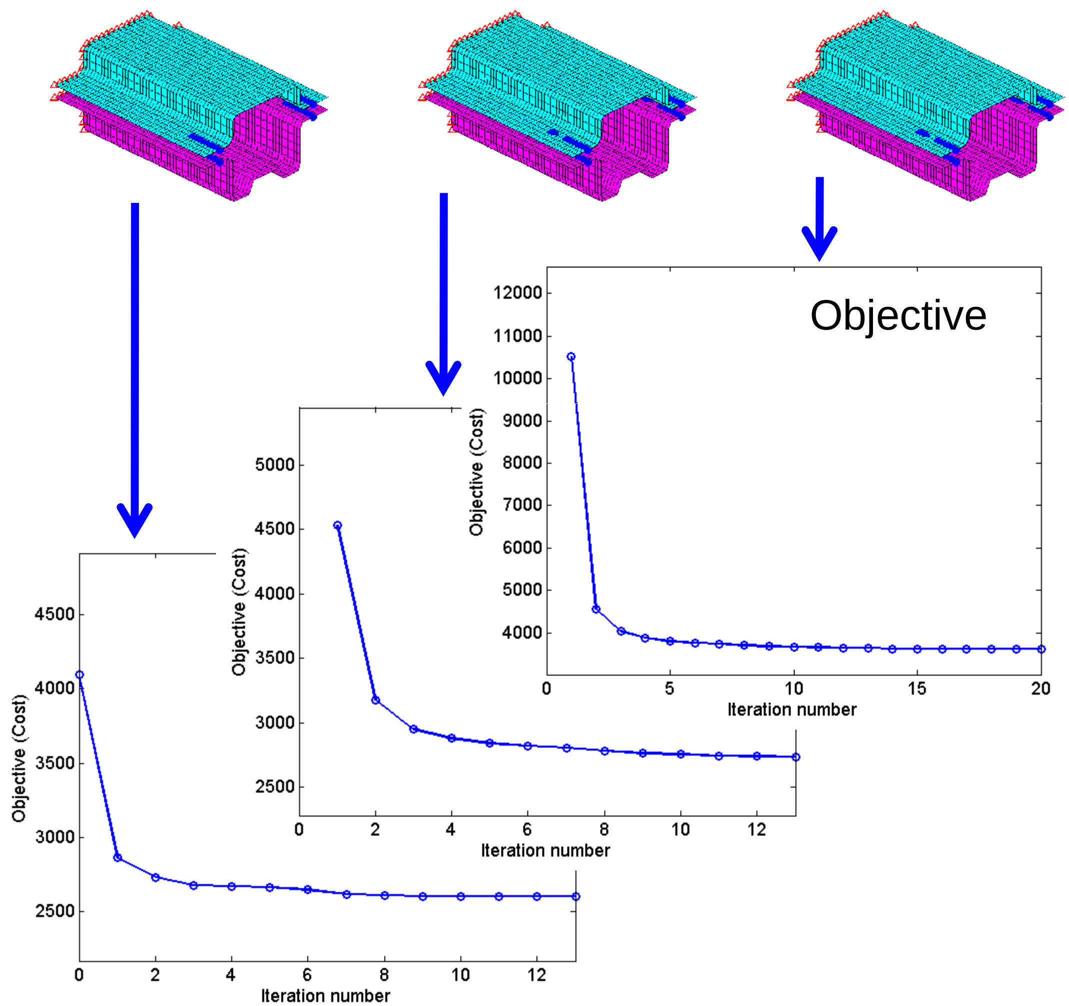
Update Rule

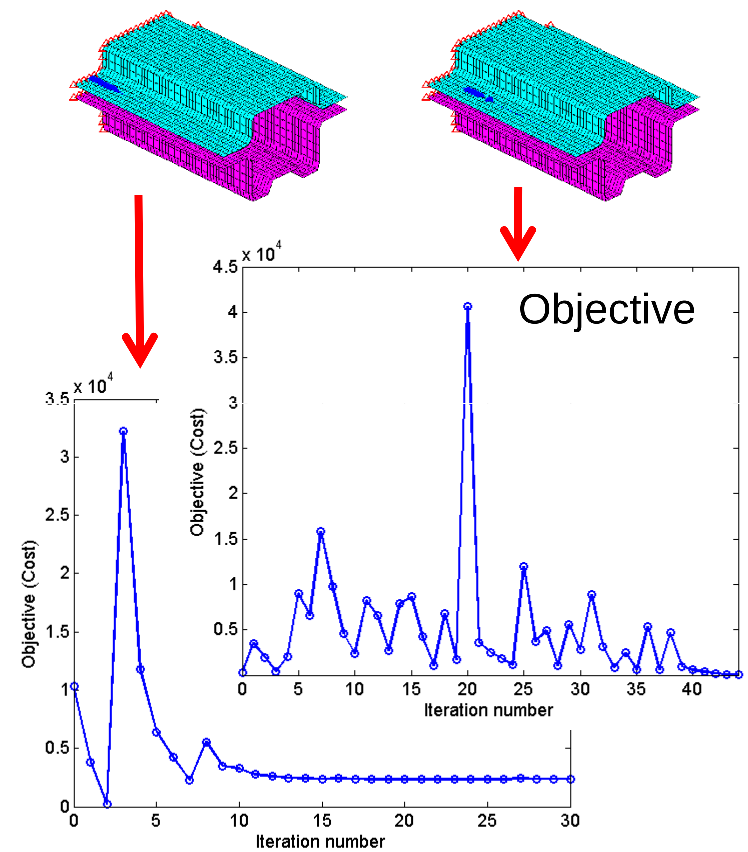
$$\rho_{K+1} = \begin{cases} \max\{(1-\zeta)\rho_K, \rho_{min}\} & \text{if} \quad \rho_K B_K^\eta \le \max\{(1-\zeta)\rho_K, \rho_{min}\}, \\ \min\{(1+\zeta)\rho_K, 1\} & \text{if} \quad \min\{(1+\zeta)\rho_K, 1\} \le \rho_K B_K^\eta, \\ \rho_K B_K^\eta & \text{otherwise.} \end{cases}$$

Opt. results: single-freq. excitation

- Joining Topology for $N \leq 20$

15Hz 30Hz 60Hz 75Hz 90Hz

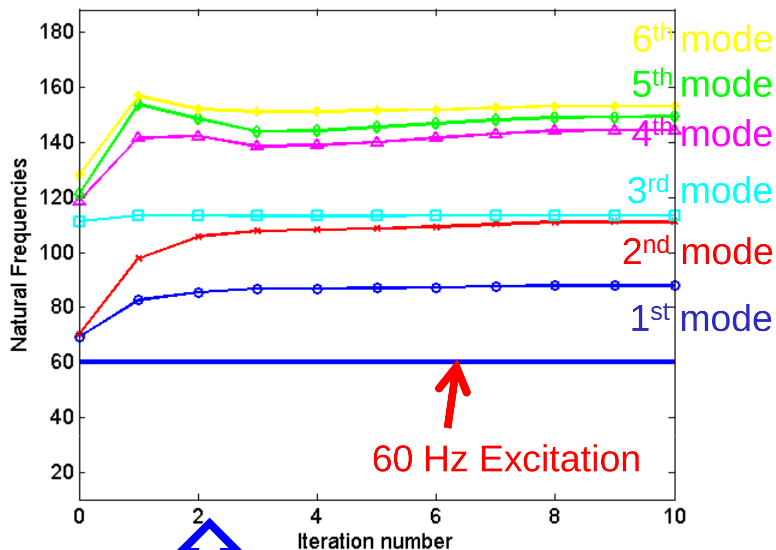


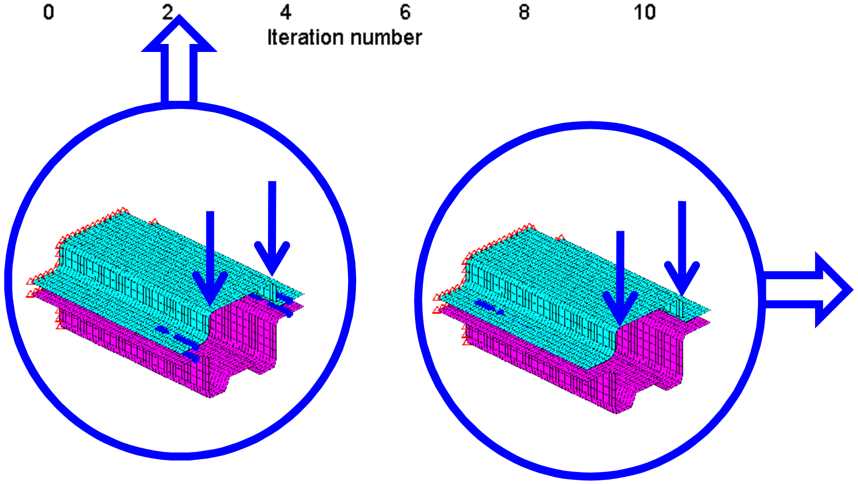


Oscillation in obj. history for higher frequencies

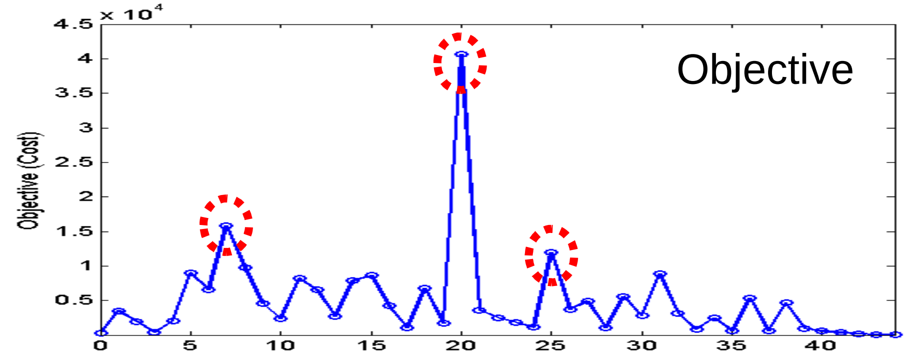
Natural freqs during optimization

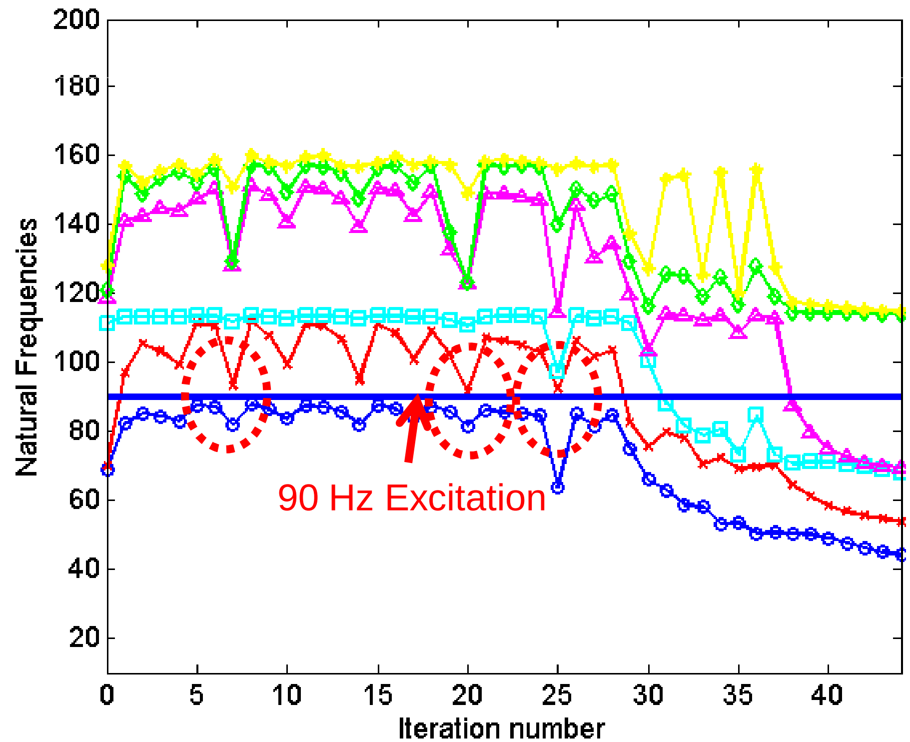
- Smooth Convergence Case (f_{ext} < 60 Hz)





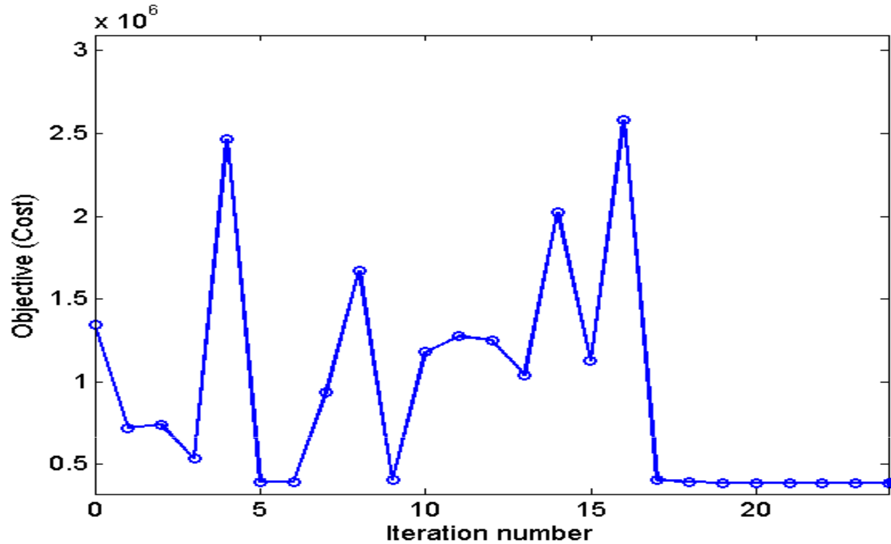
- Non-Smooth Case (f_{ext} ≥ 60 Hz)

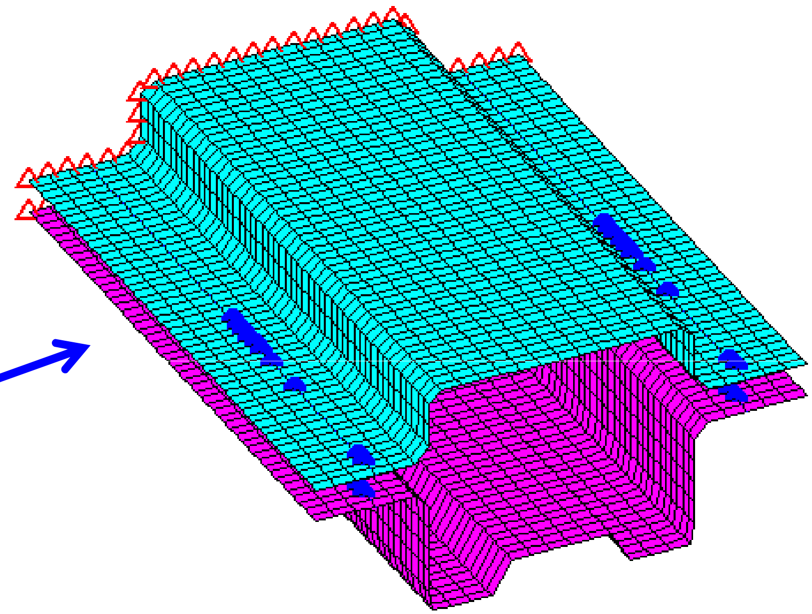




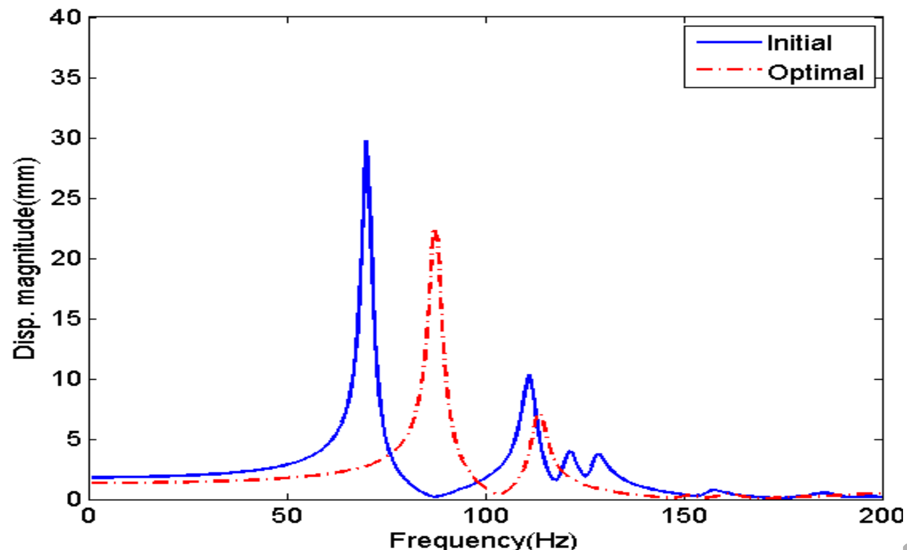
Opt. results: 50-100 Hz excitation

- Resulting topology and response





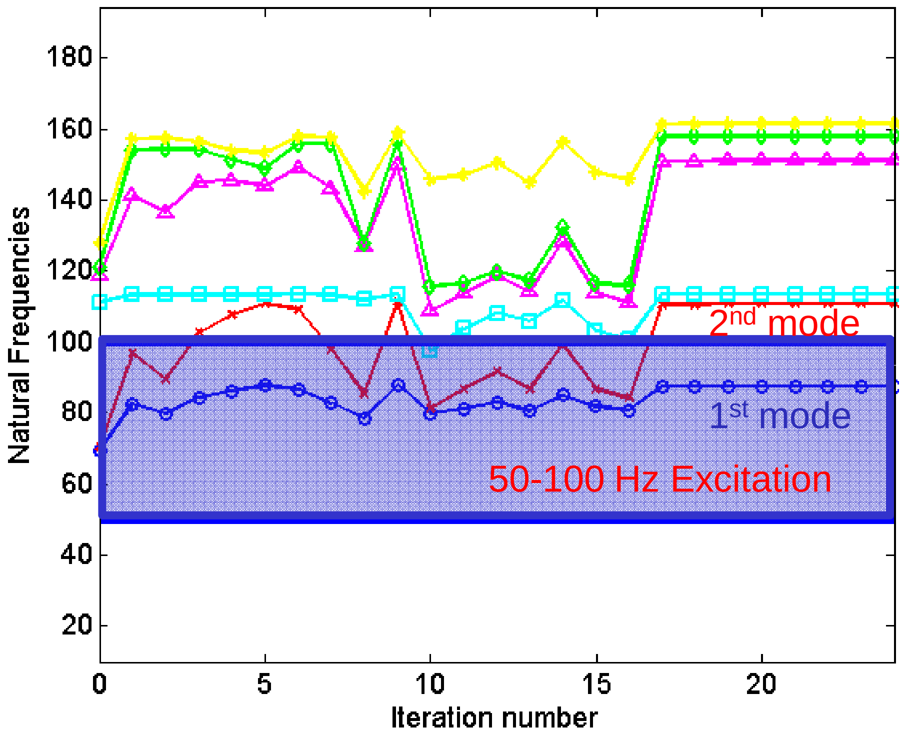
Final configuration



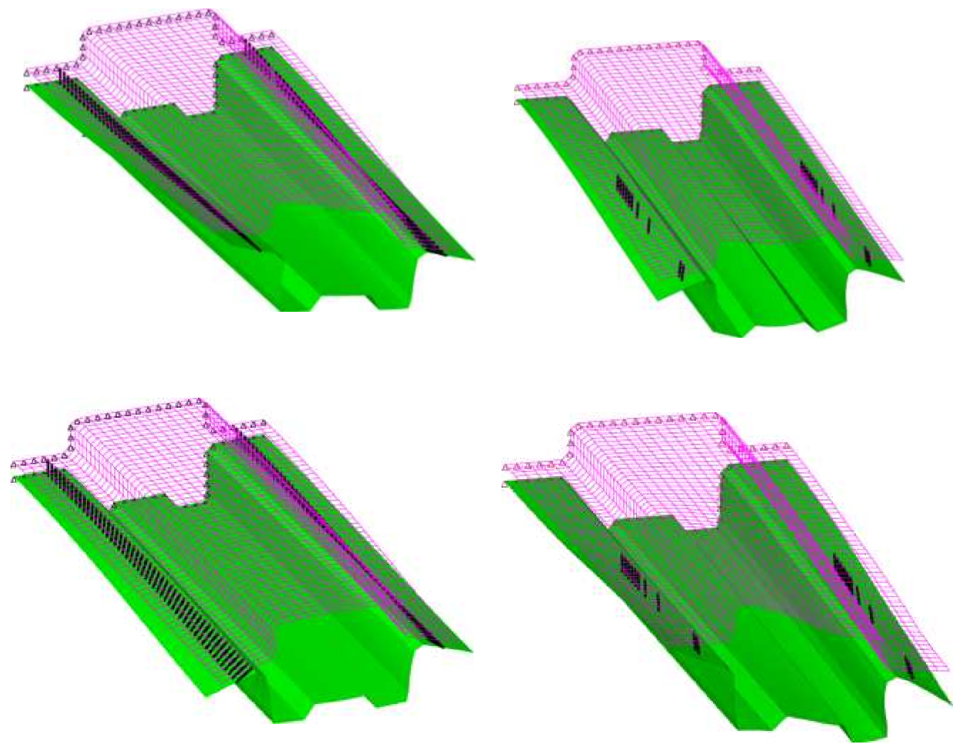
Initial configuration

Modes during optimization

- Natural frequencies during optimization



1st mode 1st mode



2nd mode 2nd mode

Initial configuration **Final configuration**

Summary

- Component mode synthesis approach was used to:
  - Generate small ROMs for fast system-level analysis
  - Retain joining locations as physical DOF for design purposes
- Topology optimization was applied to joining design to achieve system-level structural performance targets
- Optimization results were obtained for a simple example structure
  - Static case
  - Dynamic case -- challenges noted for optimization for dynamic performance