Mode Tracking In the Presence of Shape & Mesh Changes Using LS-OPT

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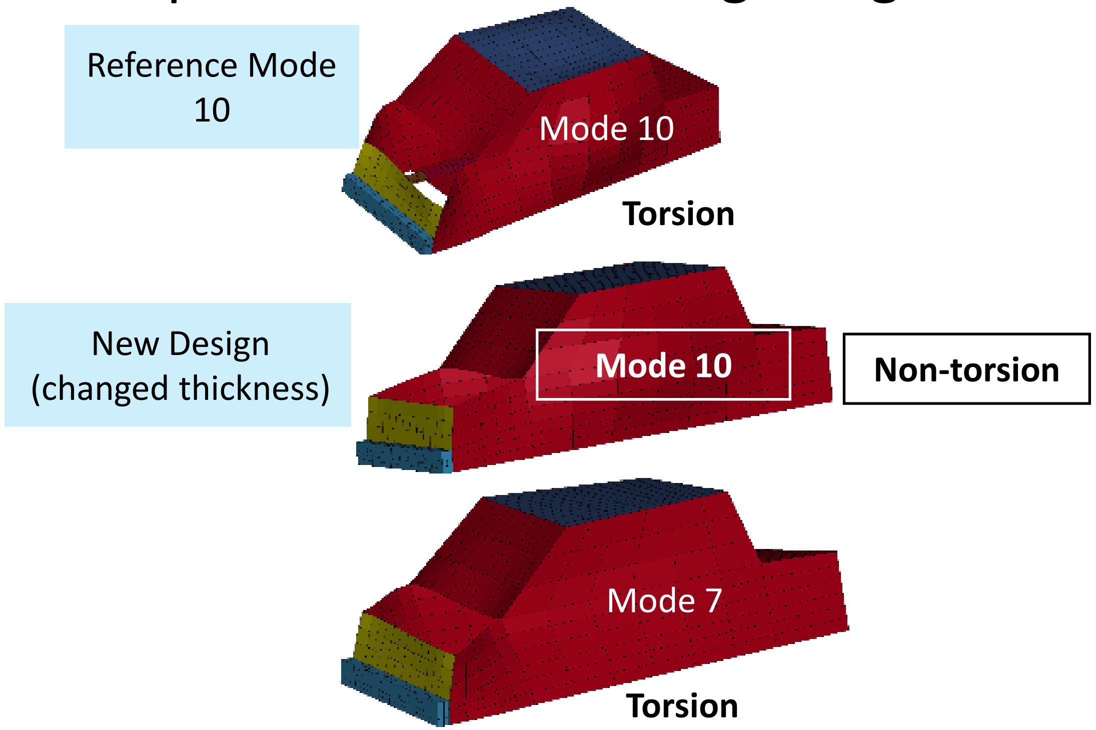
Outline

- **Importance of Mode Tracking**
- **Mode Tracking Criterion – Modal Assurance Criterion (MAC)**
- **Challenges due to Shape Changes and Remeshing**
- **Interpolated Modal Assurance Criterion (IMAC)**
  - **Point Set Registration (Coherent Point Drift)**
  - **Interpolation of Modal Eigenvector Components**
- **Examples**

LS-OPT: Mode Tracking in the Presence of Shape and Meshing Changes

- Mode tracking is needed if a particular shape is of interest during design



- No way to know beforehand that the new design will have mode 7 as torsional mode instead of 10.

- ***<u>Modal Assurance Criterion (MAC)</u>*** *used to identify similar modes in LS-OPT*
  - *Based on vector operations over eigenvector corresponding to the baseline mode of interest and each eigenvector of the new design*
  - *New design eigenvector with highest MAC is identified as being most similar to reference mode shape*

Reference mode

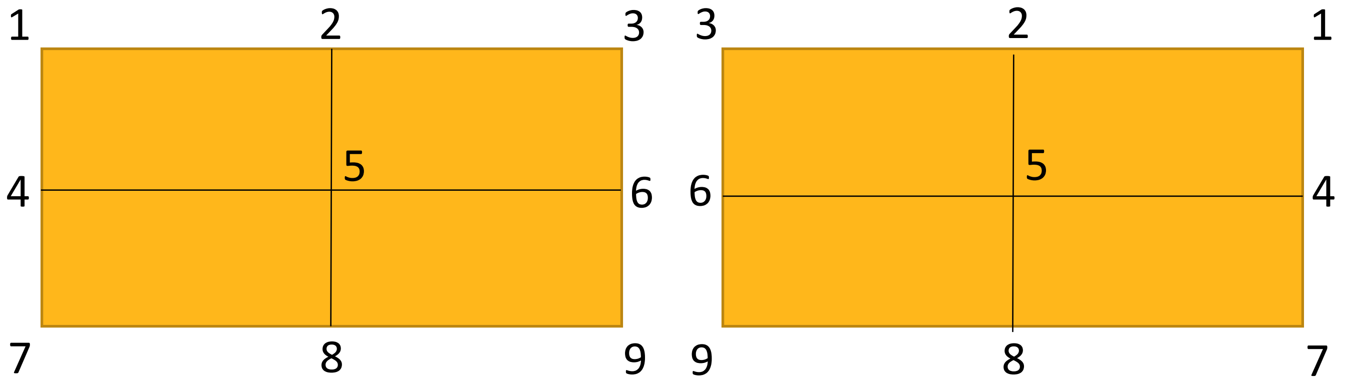
Compared mode

$$\max_j \frac{\{\varphi_0\}^H \{\varphi_j\}\{\varphi_j\}^H \{\varphi_0\}}{\{\varphi_0\}^H \{\varphi_0\}\{\varphi_j\}^H \{\varphi_j\}} = \max_j MAC_j$$

Eigenvectors φ_0 and φ_j must have same length and node order

<u>Current Mode Tracking</u> using Modal Assurance Criterion (MAC) in LS-OPT ***<u>requires identical mesh</u>*** for eigenvector comparison.

Incompatible Vectors for MAC Calculation Due to Re-meshing



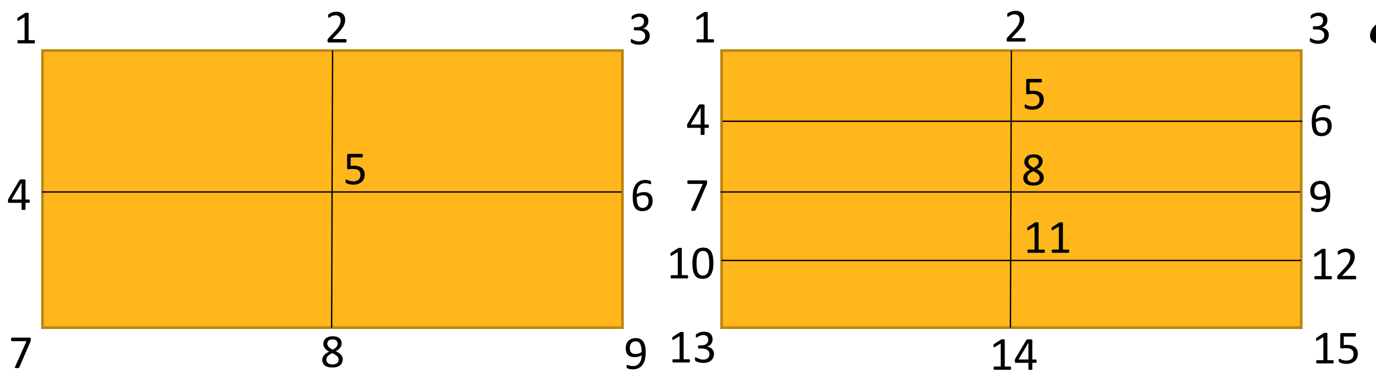
Reference mode

Compared mode

$$\max_j \frac{\{\varphi_0\}^H \{\varphi_j\} \{\varphi_j\}^H \{\varphi_0\}}{\{\varphi_0\}^H \{\varphi_0\} \{\varphi_j\}^H \{\varphi_j\}} = \max_j MAC_j$$

$$\boldsymbol{\varphi}_0 = \{v_{01}, v_{02}, v_{03}, v_{04}, v_{05}, v_{06}, v_{07}, v_{08}, v_{09}\}^T$$

$$\boldsymbol{\varphi}_j = \{v_{j3}, v_{j2}, v_{j1}, v_{j6}, v_{j5}, v_{j4}, v_{j9}, v_{j8}, v_{j7}\}^T$$



$$\boldsymbol{\varphi}_0 = \{v_{01}, v_{02}, v_{03}, v_{04}, v_{05}, v_{06}, v_{07}, v_{08}, v_{09}\}^T$$

$\boldsymbol{\varphi}_j = \{v_{j1}, v_{j2}, v_{j3}, v_{j4}, v_{j5}, v_{j6}, v_{j7}, v_{j8}, v_{j9},$ ~~$v_{j10}, v_{j11}, v_{j12}, v_{j13}, v_{j14}, v_{j15}$~~ $\}^T$

- Intuitive Interpolation (e.g. using shape functions) or node deletion
- Avoidable Re-meshing

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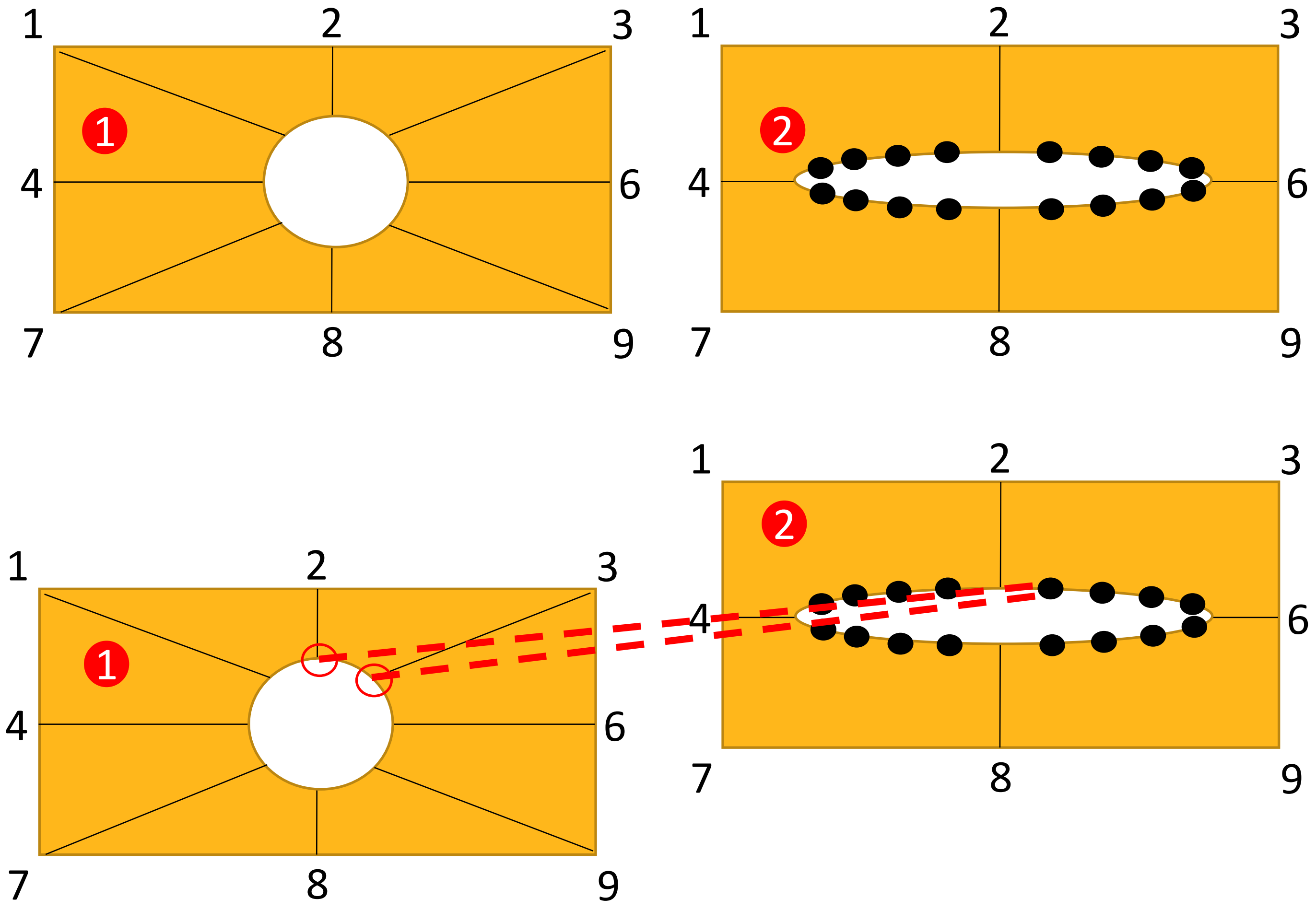
Re-meshing & Eigenvector Incompatibility Due to Shape Change



- Re-meshing can be avoided even for shape changes, but unavoidable at times
- Non-intuitive mapping
- Non-intuitive interpolation weights

- Point Set Registration (PSR) algorithm used for mapping nodes
  - Non-rigid Coherent Point Drift (CPD) method

Non-Rigid Coherent Point Drift

- Alignment of two point sets as a probability density estimation problem
- Gaussian mixture model (GMM) centroids (1st point set $\boldsymbol{Y}_{M\times D}$) fit to the data (2nd point set $\boldsymbol{X}_{N\times D}$) by maximizing the likelihood

$$p(\mathbf{x}) = \sum_{m=1}^{M} P(m) p(\mathbf{x}|m)$$

$$p(\mathbf{x}|m) = \frac{1}{(2\pi\sigma^2)^{D/2}} \exp^{-\frac{\|\mathbf{x}-\mathbf{y}_m\|^2}{2\sigma^2}}$$

- GMM centroids forced to move coherently as a group to preserve the topological structure of the point sets

- Coherence constraint imposed by regularizing the displacement field

$$\mathcal{T}(\mathbf{Y}, v) = \mathbf{Y} + v(\mathbf{Y})$$

- Regularized negative log likelihood

$$f(v, \sigma^2) = E(v, \sigma^2) + \frac{\lambda}{2} \phi(v)$$

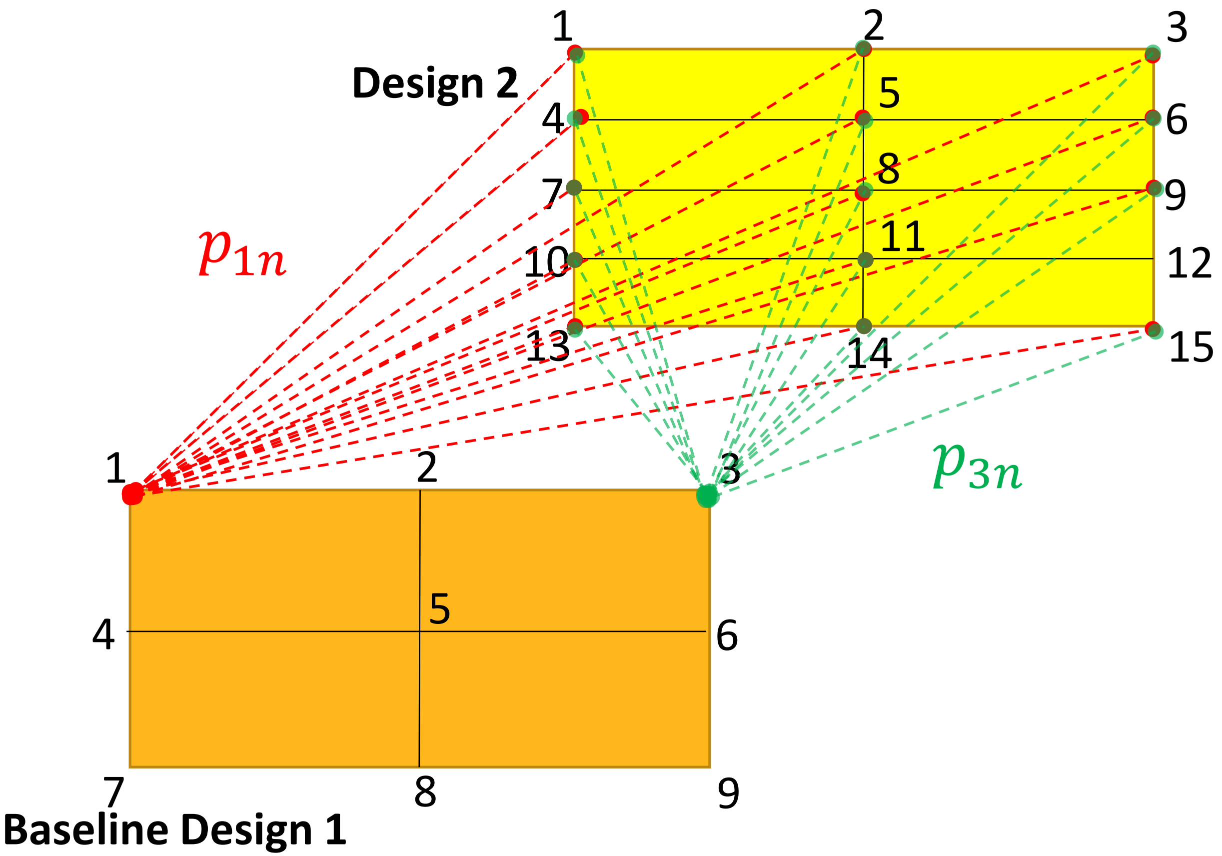
$$E(v, \sigma^2) = -\sum_{n=1}^{N} log \sum_{m=1}^{M} P(m) P(\boldsymbol{x}_n|m)$$

- v and σ^2 solved iteratively using Expectation Minimization (EM).
- *Pairwise probability of association between nodes of the two sets*

Myronenko A, Song X. Point set registration: Coherent point drift. IEEE transactions on pattern analysis and machine intelligence. 2010 Mar 18;32(12):2262-75.

Interpolated Modal Assurance Criterion (IMAC) for Mode Tracking

- *Pairwise probability of association between nodes of the two sets*



- Interpolated j[th] eigenvector

$$\hat{\varphi}_{jm} = \frac{1}{\sum_{n=1}^{N} p_{mn}} \sum_{n=1}^{N} p_{mn}\varphi_{jn} \quad (m \in [1,9])$$

$\boldsymbol{\varphi}_0 : 9 \times 1$ $\boldsymbol{\varphi}_j : 15 \times 1$ $\hat{\boldsymbol{\varphi}}_j : 9 \times 1$

- Interpolated MAC measure for design 2 (φ_0 and $\hat{\varphi}_j$ length = m)

$$IMAC_j = \frac{\varphi_0^H \hat{\varphi}_j \hat{\varphi}_j^H \varphi_0}{\varphi_0^H \varphi_0 \hat{\varphi}_j^H \hat{\varphi}_j}$$

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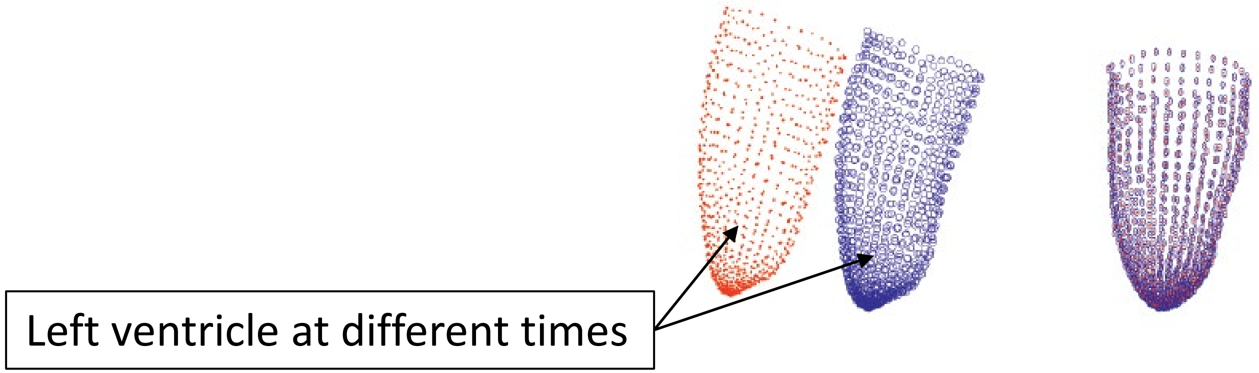
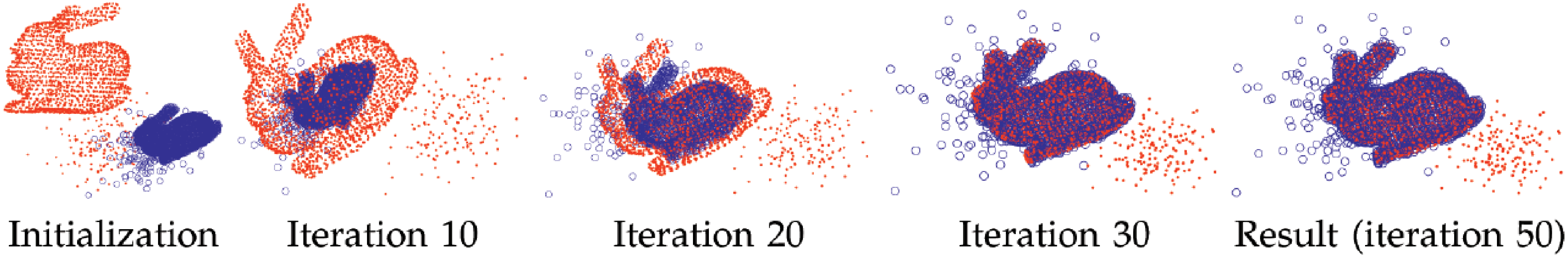
Examples of CPD PSR





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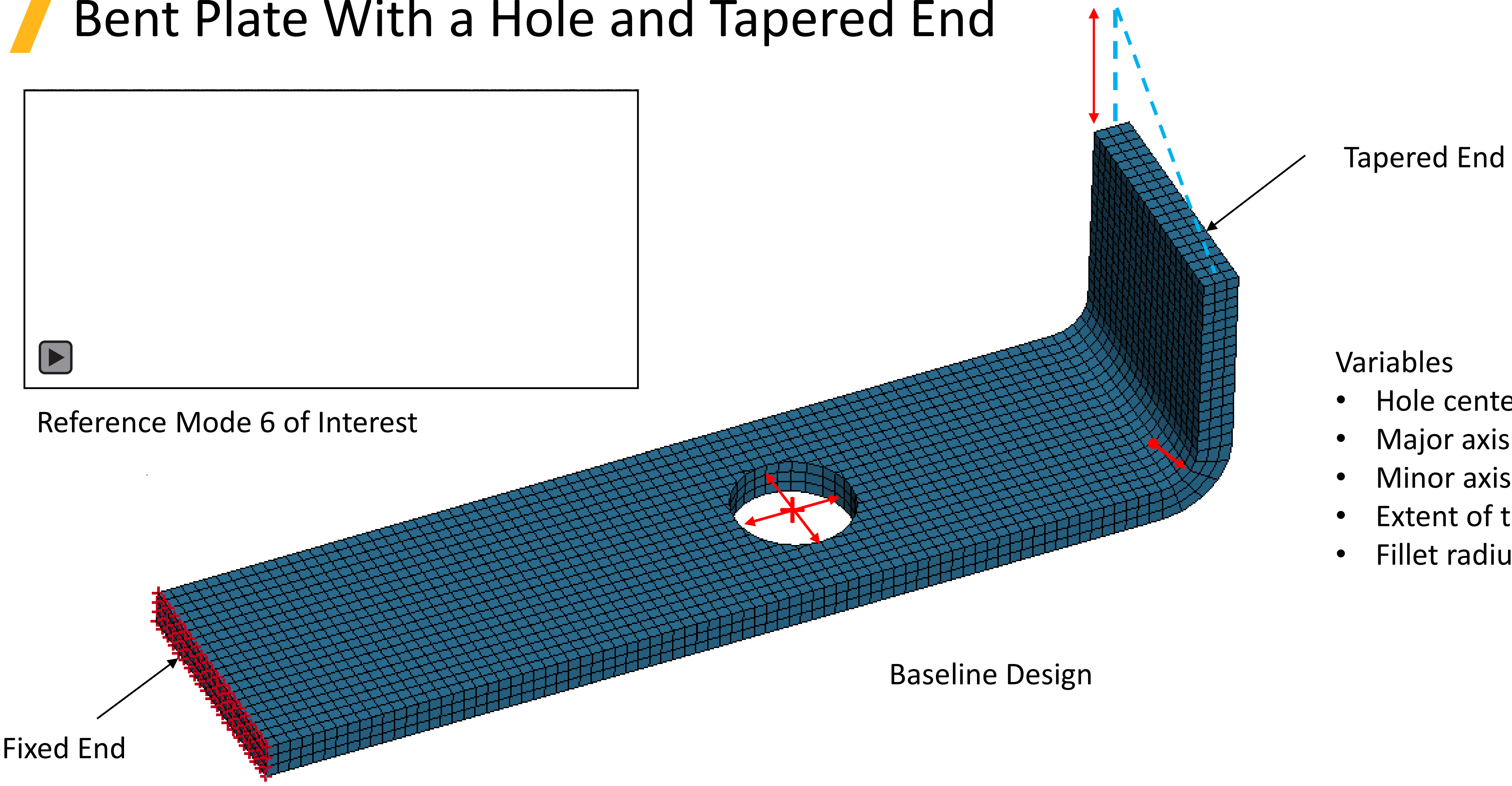
Bent Plate With a Hole and Tapered End

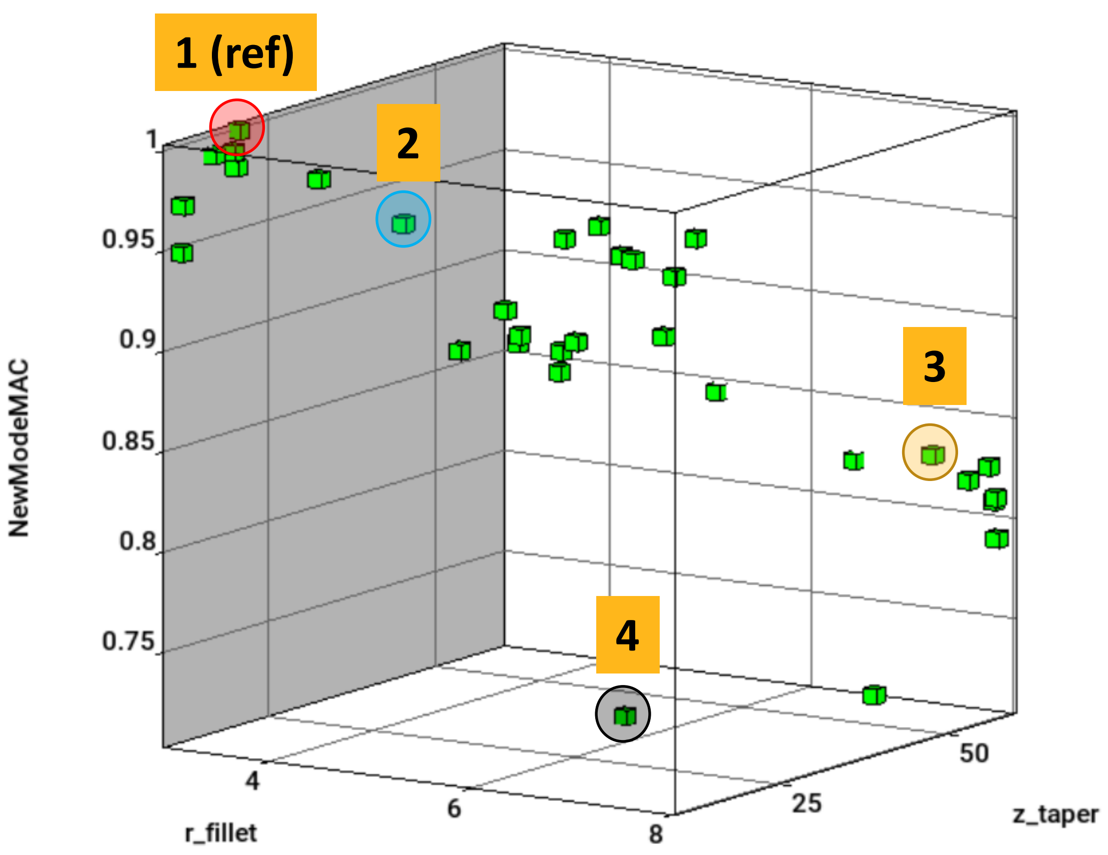
Reference Mode 6 of Interest

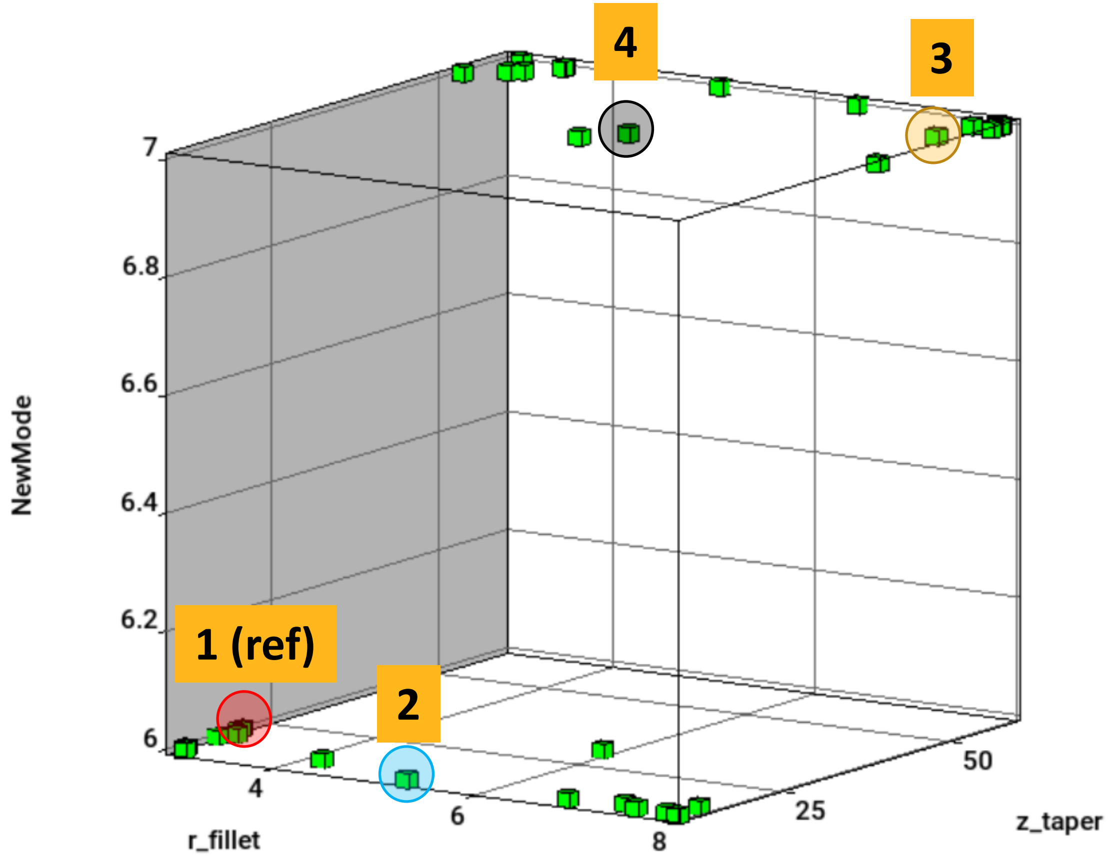


Baseline Design

Variables
- Hole center position
- Major axis
- Minor axis
- Extent of taper
- Fillet radius

Bent Plate With a Hole and Tapered End: New Modes & MAC





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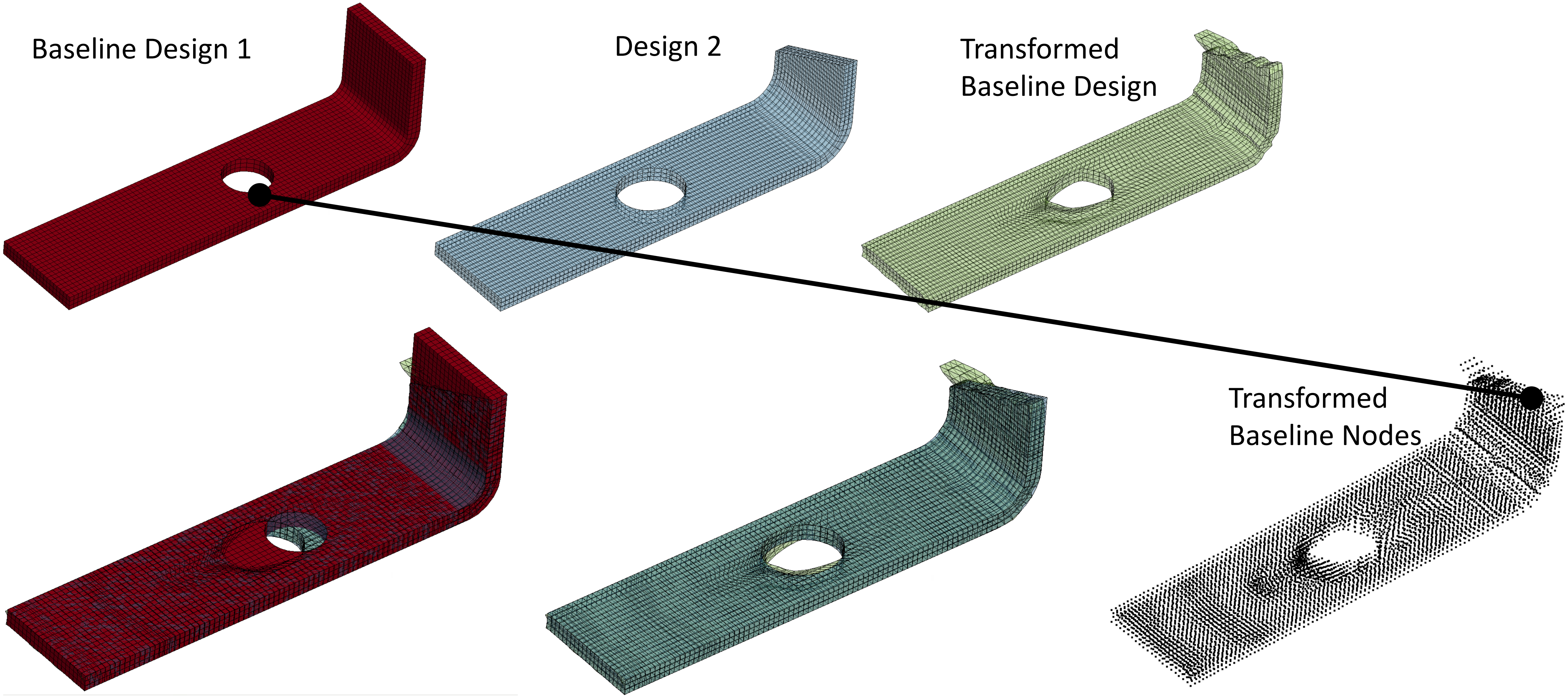
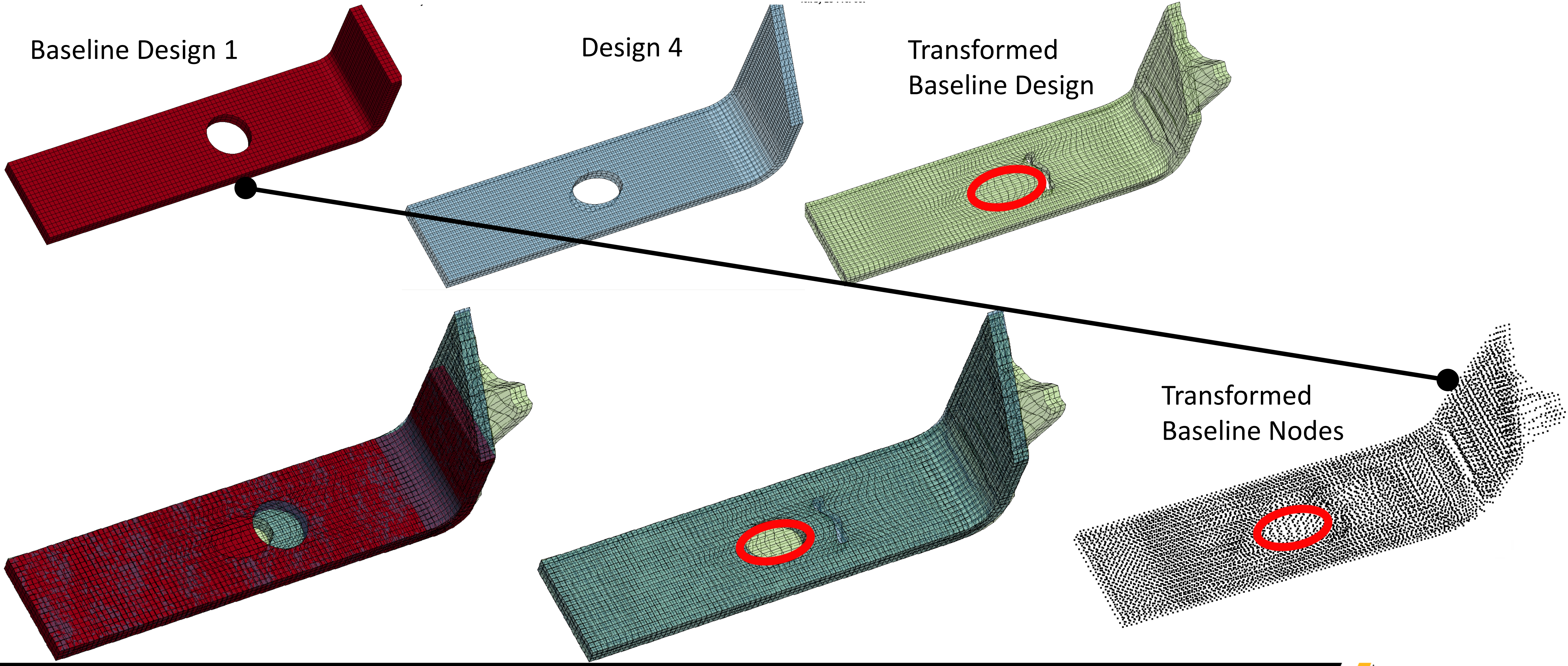
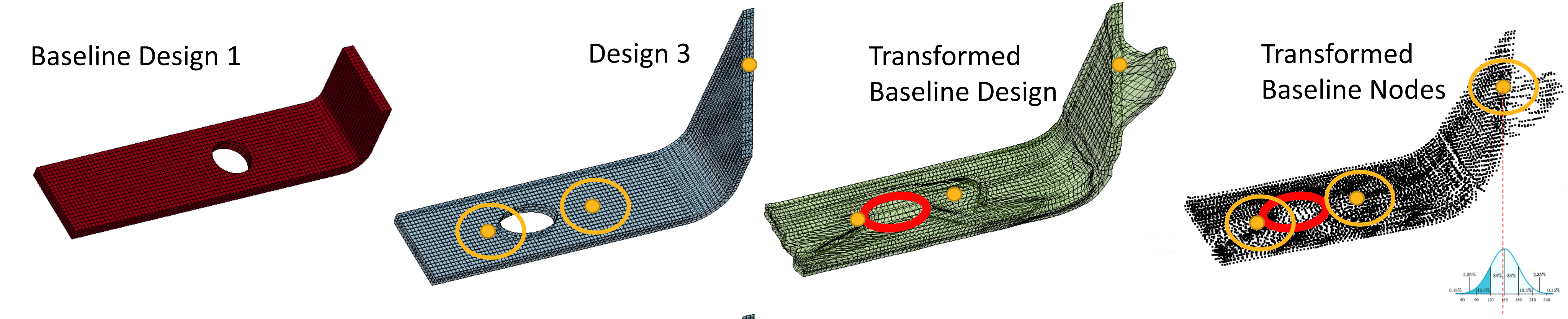
Bent Plate With a Hole and Tapered End: Design 2 Mapping

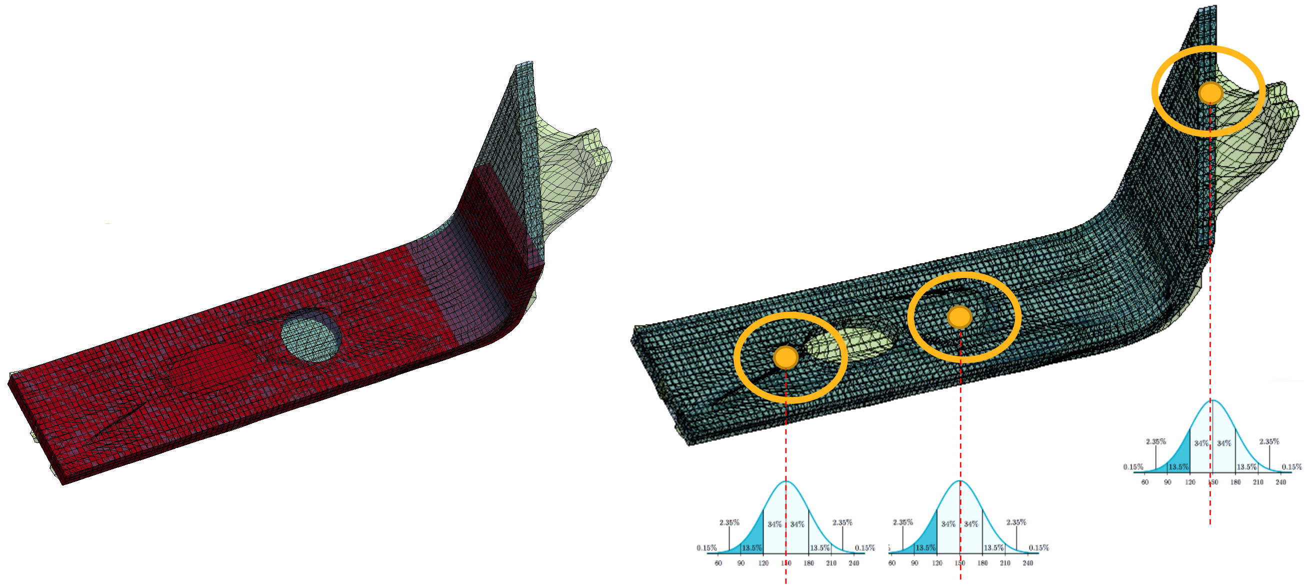


Bent Plate With a Hole and Tapered End: Design 4 Mapping



Bent Plate With a Hole and Tapered End: Design 3 Mapping





- There are still some points in regions that should be empty after transformation.
- Such points are spaced out (lower density)

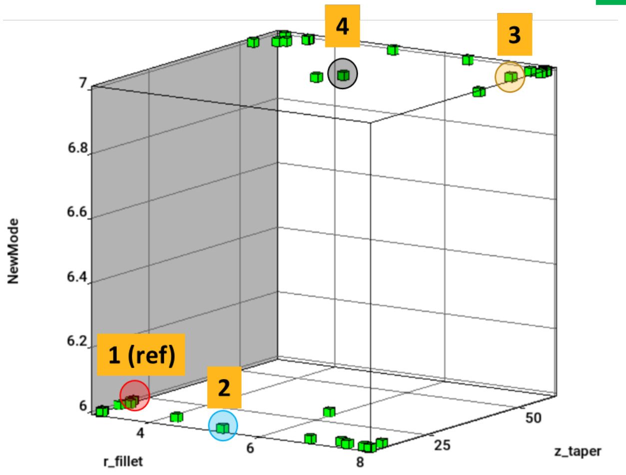
- As distance increases, weightage decreases
- The outlier points have minimal effect
- The transformed mesh isn't used for FE analysis
- Originally empty regions are filled up nicely

Matched Mode Shapes Using IMAC

1 2 3 4

Design 1 Modes 1-8

5 6 7 8



Design 2 Mode 6

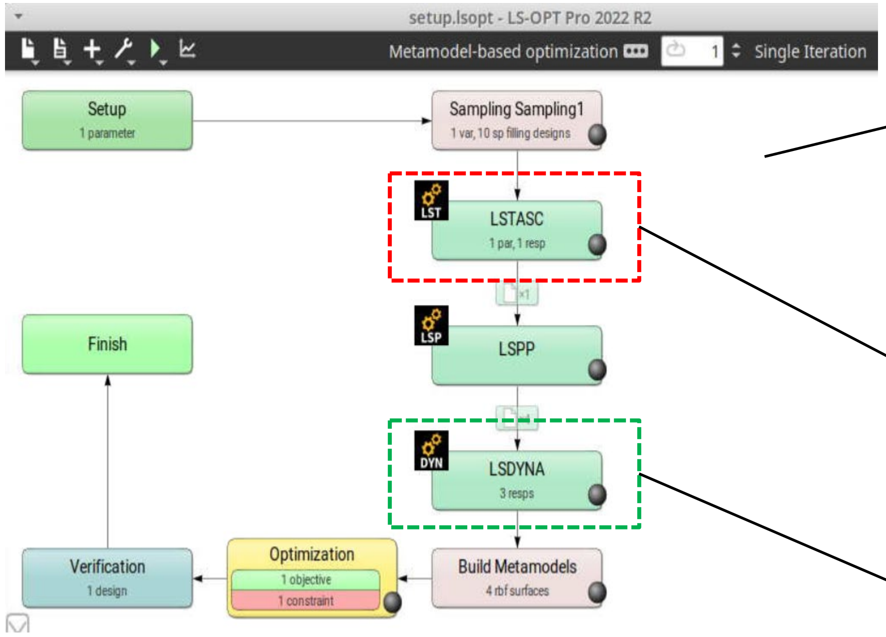
Design 3 Mode 7

Design 4 Mode 7

LS-OPT Mode Tracking with LS-TaSC Topology Optimization

NVH Optimization

- LS-OPT features with LS-TaSC to unlock complex design schemes
- NVH constraint for topology optimization handled using LS-OPT
- Multilevel optimization problem with global and local variables
  - LS-OPT variables: Design part mass fraction
  - LS-TaSC variables: Element densities

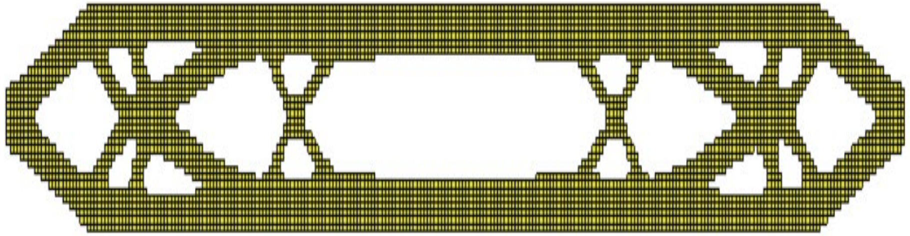


Global problem:
Minimize total mass with bending frequency constraints and part mass fraction variables

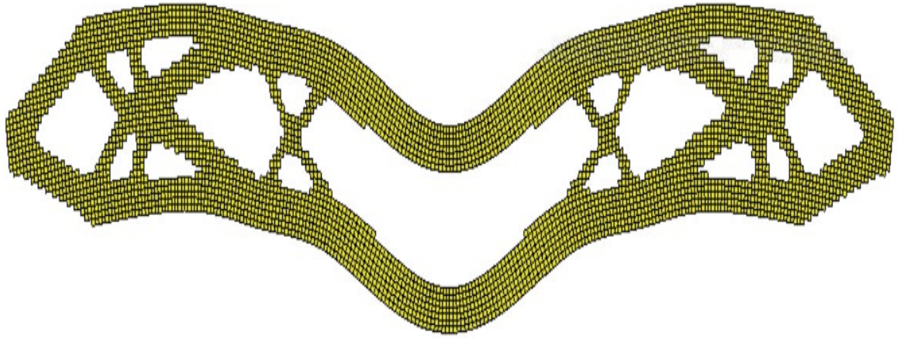
Local problem:
Unconstrained topology optimization at constant mass fraction with element density variables

Eigenvalue analysis of optimized topology

Simple Plate Model

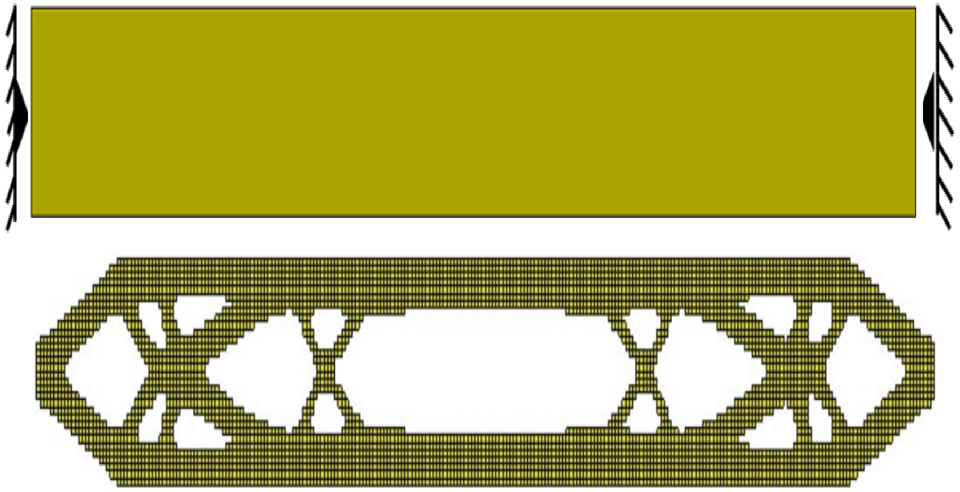


Optimized topology at baseline mass fraction

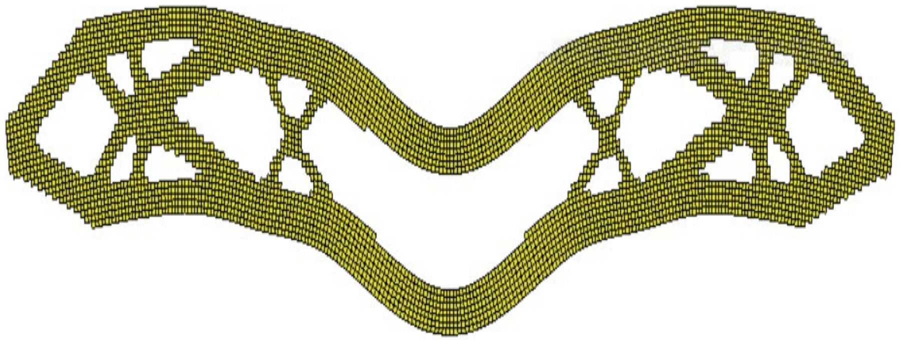


Interested mode shape

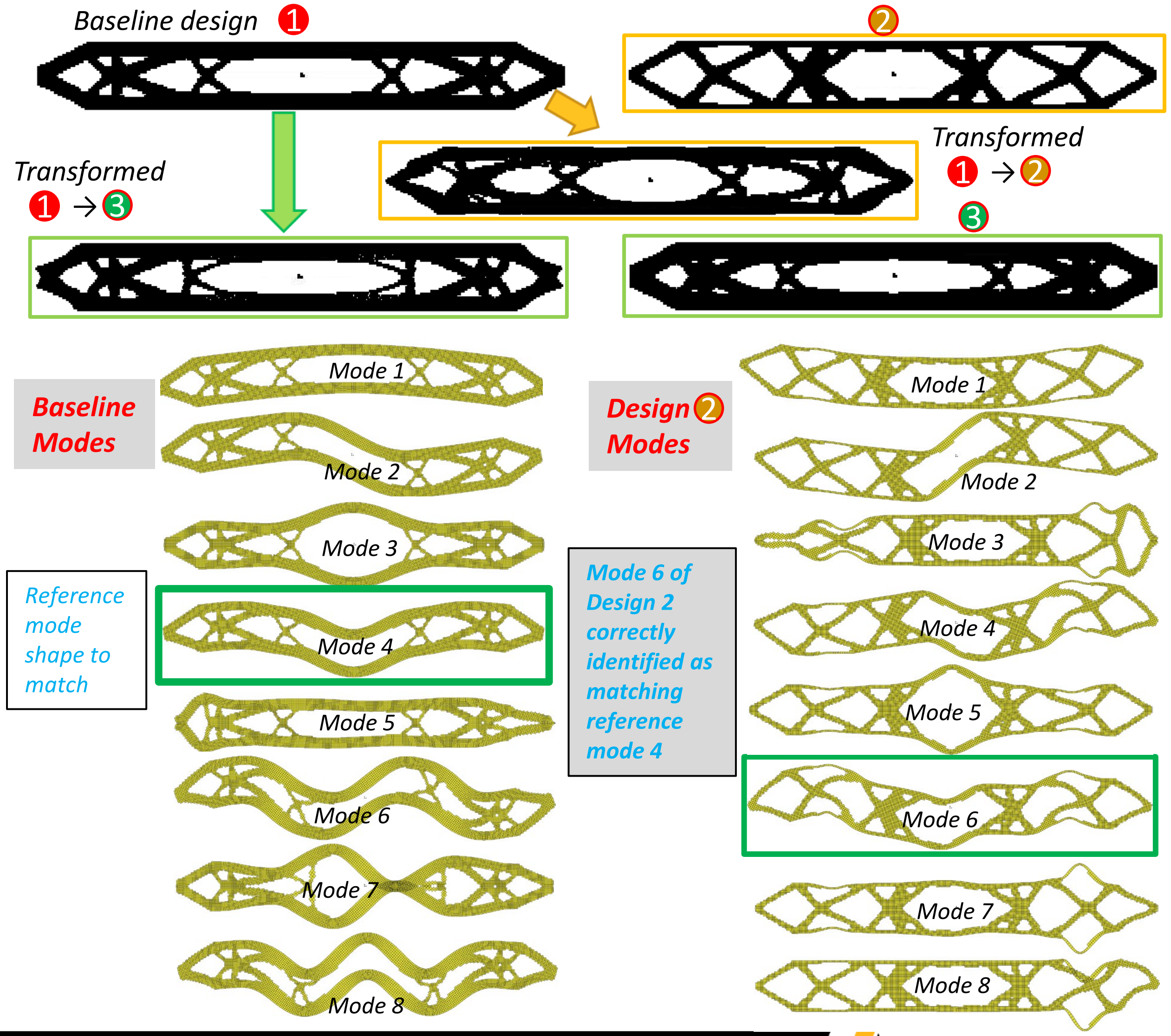
LS-OPT Mode Tracking with LS-TaSC Topology Optimization



Optimized topology at baseline mass fraction

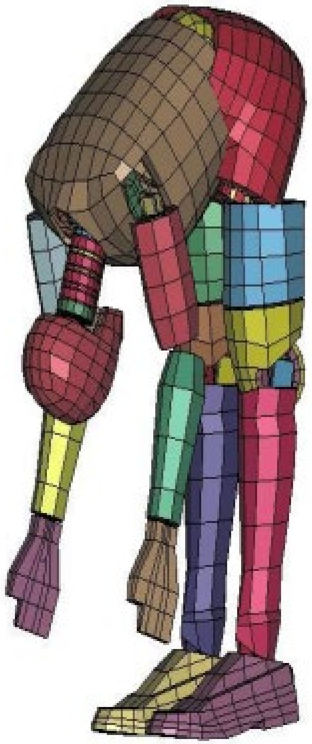


Interested mode shape



Summary and Future Work

- Mode tracking based on MAC has been available in LS-OPT for quite some time, but is limited to designs with same mesh
- Changes in shape and mesh require special handling
- Interpolated MAC (IMAC) based on mapping non-identical sets of nodes has been implemented
- Based on non-rigid Coherent Point Drift (CPD)
- Available in 2023R1
- Work on improving performance is ongoing.



Thank you!!