Topology and Shape Optimization with Abaqus
Overview

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- What optimization is
- What ATOM does
- Where ATOM fits in

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- ATOM integration in Abaqus/CAE

Key ATOM Concepts
- Design Responses
- Objective functions
- Constraints
- Manufacturing using Geometric Restrictions

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ATOM Summary and Benefits
Introduction

Abaqus Topology Optimization Module (ATOM) is a new product, launched with the release of Abaqus 6.11.

Product features:

- Topology Optimization – removes volume to find more efficient topologies.
- Shape Optimization – moves nodes to smooth peak stresses or other objectives.

ATOM = Optimizer + Abaqus

- Parts and Assemblies
- Large deformation
- Contact
- Non-linear materials
- Manufacturing restrictions
- Export results to CAD
Topology Optimization

“Topology optimization is a phrase used to characterize design optimization formulations that allow for the prediction of the lay-out of a structural and mechanical system. That is, the topology or ‘landscape’ of the structure is an outcome of the procedure.” - Martin P. Bendsøe and Ole Sigmund

- How does ATOM achieve this?
  - Given an initial material distribution (left), topology optimization produces a new landscape (right) by scaling the relative densities of the elements in the design domain.
  - Elements with large relative densities are retained (shown in green) while those elements whose relative densities have become sufficiently small are assumed to be voids. Thus a new “landscape” is obtained.
Shape optimization refers to procedures that result in the prediction of a boundary (or shape) of the design domain of the structural/mechanical system to be optimized.

- How does ATOM achieve this?
  - In a finite element analysis, nodes on the boundary are displaced in order to achieve an objective (minimization of stress on the surface for example).
  - Thus, a new shape is obtained.
SIMULIA’s Design Exploration and Optimization Tools

**ATOM**
Tuned for topology and shape optimization
Not feature based or non parametric
Can handle a very large number of design variables. (~100K-1000K)
Single objective optimization

**Isight**
A general purpose design exploration and optimization package
Feature based or Parametric
Meant for small number of design variables (~10-100)
Multi-objective, multi-discipline optimizations possible
ATOM Workflow

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Solver Iterations

- **Iterative process**
  - Each Abaqus job can be parallel

- **Topology optimization**
  - Scale material density

- **Shape optimization**
  - Move nodes

- ~50 solver iterations is typical

Afterwards, export to CAD in INP or STL format
The flow chart on the left shows the user actions required to setup the optimization. Each user action is associated with a manager in the Optimization module accessible from the Optimization Module Toolbox or the Model Tree.
Once an Optimization Task is set up, an Optimization Process needs to be defined to execute the optimization.

Users may have multiple Abaqus models and optimization tasks defined. An optimization process refers to a unique Model and Task combination.

Right-click on the optimization process to access: Validate, Submit, Restart, Monitor, Extract and Results postprocessing.
ATOM Workflow: Results Visualization

The Abaqus Visualization module allows for convenient visualization of optimization results.

Create Model
Create Optimization Task
Create Design Responses
Create Objective Functions
Create Constraints
Create Optimization Process
Submit Optimization Process

Optimization Processes (2)
- Opt-Process-2 (Completed)
- gr8 (Check Completed)

Switch Context Ctrl+Space
Edit...
Copy...
Rename...
Delete...

Validate
Submit
Restart
Monitor...
Extract...

Results
Set As Root
Expand All Under
Collapse All Under

Abaqus Analysis
Monitor Optimization Progress
Monitor Job Progress

Prepare Design Variables and Update Finite Element Model

Optimization complete

YES

NO

Review results

Optimization Process is finished
Relaxation and Penalization

In order to apply gradient-based optimization techniques (which can be more efficient), the integer value problem is relaxed.

The design variables (relative densities) are assumed to be continuous.

\[ \min_p: u_{out} \]

Subject to:
\[ \sum_{e=1}^{n} v_e \rho_e \leq V \]
\[ 0 \leq \rho_e \leq 1 \]
Equilibrium equations

How do we interpret the intermediate density elements?
- We don’t! We use an approach that penalizes intermediate density elements so that they are not favorable in the final solution.
Creating an Optimization Task

An Optimization Task identifies the type of optimization and the design domain for the optimization.

The task serves to configure the optimization algorithm to be used:
- Create an optimization task from the model tree or the optimization toolbox as shown
- Choose the Optimization task type accordingly

Each task contains design responses, objective functions, constraints, geometric restrictions and stop conditions.
Optimization Task – Design Responses

- Single or multiple terms
- Region based
- Select the step to extract results from or load cases

Operators:
- Sum
- Minimum
- Maximum
- Deviation from Max
- Number of values

E.g. “sum the element strain energy”
Objective Functions can be created from any previously defined Design Responses

- Allows combining multiple Design Responses
- Further, the Objective Function is always a weighted sum of the Design Responses specified in the Objective Function editor
- Reference values are constants subtracted from the Design Response
- Targets:
  - Minimize, Maximize, Minimize the maximum weighted difference from the maximum
Optimization Workflow – Constraints

- Uses already defined Design Response’s
- Allows constraining the Design Response to:
  - Greater than
  - Greater than a fraction of the initial value
  - Less than
  - Less than a fraction of the initial value

E.g: “Constraint the volume to be less than 35% of the original volume”
Geometric Restrictions are additional constraints enforced independent of the optimization

- Geometric restrictions can be used to enforce symmetries or minimum member sizes that are desired in the final design.
- Demold control is perhaps the most important geometric restriction. It enables the user to place constraints such that the final design is manufacturable.
Geometric Restrictions: Overview

The following geometric restrictions are available:

- Frozen areas
- Member Size
- Demolding
- Cyclic symmetry
- Planar, Point and Rotational Symmetry

Contact and Rotational Symmetry
If the topology obtained from the optimization is to be produced by casting, the formation of cavities and undercuts need to be prevented by using demold control.

- **Demold region**: region where the demold control restriction is active.
- **Collision check region**: region where it is checked if a removal of an element results in a hole or an undercut.
  - This region is same as the demold region by default.
  - This region should always contain at least the demold region.
- **Pull direction**: the direction in which the two halves of the mold would be pulled in (as shown, bottom right).
- **Center plane**: central plane of the mold (as shown, bottom right).
  - Can be specified or calculated automatically.

![Edit Geometric Restriction](image1)

![Pull directions](image2)
Geometric Restrictions: Demold Control

**Stamping** option enforces the condition that if one element is removed from the structure, all others in the ± pull direction are removed too.

- In the gear example, a stamping constraint was used to ensure that only through holes are formed.

**Forging** is a special case of casting. The forging die needs to be pulled only in one direction.

- Forging option creates a fictitious central plane internally on the back plane (shown below) so that pulling takes place in only one direction.
Comparison with/out manufacturing constraints

With forging constraint

Without any manufacturing constraint
Symmetry

- Topology Optimization of symmetric loaded components usually leads to a symmetric design.
- In case we want a symmetric design but the loading isn’t symmetric, it is necessary to enforce symmetry.
Frozen area constraints ensure that no material is removed from the regions selected as frozen (relative density here is always 1)

- These constraints are particularly important in regions where loads and boundary conditions are specified since we don’t want these regions to become voids.
- In the gear example, the gear teeth and the inner circumference were kept frozen. We didn’t want to lose contact with the shaft or loose the load path.
Additional geometric restrictions are available in shape optimization that help maintain manufacturability.

Geometric restrictions unique to shape optimization are:

- Turn control
- Drill control
- Stamp control
- Growth
- Design direction
- Penetration check
- Slide region control
ATOM Execution and Monitoring

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Manufacturing using Geometric Restrictions

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Execution

- New Process (similar to Adaptivity or Co-execution)
- Restart a stopped analysis run
- Allows control on maximum number of jobs, results ODB merge, etc.
- Abaqus/CAE queues are supported (LSF/etc)
Monitoring

- Log shows the optimization progress iteration by iteration
- Errors/Warning can be tracked
- ATOM output file is exposed for more advanced users
- Abaqus jobs can be monitored from within the Optimization monitor
Postprocessing

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ATOM Summary and Benefits
An ODB is created during the optimization, merging Abaqus results from each individual optimization iteration Abaqus analysis.

Complete Abaqus results are provided from Iteration 0.

The ATOM_OPTIMIZATION step contains optimization output from each optimization iteration.

A new _Optimization step is created for each Abaqus step and results from the last iteration or first mode are saved for each optimization iteration.

A frame is created in each optimization step for each iteration to track optimization iterations as history.
Postprocessing For Topology Optimization

A cut based material fraction is automatically created to show the resulting design surface.
Postprocessing for Shape Optimization

ATOM performs shape optimization by modifying the node locations defined for Abaqus input for each iteration.

ATOM post processing tracks these modifications as offsets from the original configuration (vector field variable DISP_OPT).

The DISP_OPT offsets are automatically added to the nodal locations when viewing the model in optimization steps.
History Output

Use the History output variables in Abaqus/CAE to monitor constraints and Objectives.
Ensure that the optimization constraints have been satisfied within tolerance
- Optimization_report.csv is created in the working directory

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Bridge design
Comparing the topology optimization result to well established designs
ATOM Example : Pull Lever on a Press

Lever is redesigned to retain stiffness, with reduced weight

Initial volume → FEA model → Design → Validate

Proposal
Example: Shape optimization

Even small shape variations can lead to large changes in the objective

- E.g: Small changes in shape can reduce peak stresses by as much as 25% or even more.
ATOM Summary and Benefits

ATOM is a new product in Abaqus 6.11
Provides advanced capabilities for **nonlinear** structural optimization
Shortens design cycles and enables faster time-to-market
Provides engineers and product designers with:
- Manufacturable designs which meet their structural needs
- Improved design performance
- Reduces costs associated with weight/mass