Implizite Berechnungen mit LS-DYNA

- Einführung und Anwendungsbeispiele -

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Motivation: Why Implicit?

- **prestressed**, **quasi statically loaded** structures
- **long duration** analysis > 200 ms
- **different time scales** in process
  e.g. static loading followed by transient loading
  or transient loading followed by static loading
- **applications**
  e.g. metalforming, roof crush, door sag, dummy seating, ...

➡ **LS-DYNA provides explicit and implicit solution schemes**

- **one data structure**
- **one input / output**

Explicit vs. Implicit (Dynamics)

$$\rho\,\mathbf{u}_{,tt} = \nabla \cdot \boldsymbol{\sigma} + \mathbf{f}$$

explicit

$$\mathbf{M}\mathbf{a}_n = \mathbf{f}_n^{ext} - \mathbf{f}_n^{\text{int}}$$

- solution: directly
- decoupled: efficient, fast
- many small time steps
- conditionally stable (Courant)
- equilibrium?

short time dynamics:
high frequency response,
wave propagation

➡ impact, crash, ...

implicit

$$\mathbf{M}\Delta\mathbf{a}_{n+1} + \mathbf{K}\Delta\mathbf{u}_{n+1} = \mathbf{f}_{n+1}^{ext} - \mathbf{f}_n^{\text{int}} - \mathbf{M}\mathbf{a}_n$$

- solution: iteratively
- linearization necessary
- few large time/load steps
- unconditionally stable
- equilibrium! convergence?

structural dynamics:
low frequency response,
vibration, oscillation

➡ earthquake, machines, ...

Types of Implicit Analyses

Linear Analysis

- static or dynamic
- single, multi-step

Eigenvalue Analysis

- frequencies and mode shapes
- linear buckling loads and modes
- modal analysis: extraction and superposition

Nonlinear Analysis

- Newton, Quasi-Newton, Arclength solution
- static or dynamic
- default LS-DYNA: static and nonlinear!

Simplified Implicit Flowchart: Terms

0. Initialisierung $\mathbf{u}^0, \dot{\mathbf{u}}^0, \ddot{\mathbf{u}}^0$
1. Zeitschleife $(t^{n+1} = t^n + \Delta t)$

   Bestimme ‘Lasten’ (Dirichletwerte, Lasten, ...) für t^{n+1}

   Initialisiere Iterationszähler $i = 0$

   2. Setze Prädiktor-Größen $\mathbf{u}_0^{n+1} = \mathbf{u}^n; \dot{\mathbf{u}}_0^{n+1} = \dot{\mathbf{u}}^n; \ddot{\mathbf{u}}_0^{n+1} = \ddot{\mathbf{u}}^n$
   3. Berechne iterationsunabhängige RHS-Anteile
   4. Iterationsschleife
      5. Berechne und assembliere die effektive RHS $\hat{\mathbf{R}}$
      6. Berechne und assembliere die effektive Steifigkeitsmatrix $\hat{\mathbf{K}}$
      7. Löse das Gesamtgleichungssystem $\Delta\mathbf{u} = \hat{\mathbf{K}}^{-1}\hat{\mathbf{R}}$ ← *linear problem*
      8. Aktualisiere die Verschiebungen, Geschwindigkeiten und Beschleunigungen
   9. Konvergenzcheck: if (*Residuum*>TOL) goto 4. else goto 10.
10. $n = n + 1$ goto 1.

nonlinear problem

Activating Implicit Analysis

Use ***CONTROL_IMPLICIT_GENERAL** to activate implicit

- specify time step size
- all other *CONTROL_IMPLICIT keywords are optional
- default is nonlinear, static analysis

Use a **double precision executable** for implicit analysis

- better convergence for nonlinear
- mandatory for linear, eigenvalue accuracy

Stiffness Matrix requires lots of **memory**

- huge speed penalty for out-of-core jobs

ls-dyna i=input.k memory=200m

200,000,000 words:
800 Mbytes in single precision
1600 Mbytes in double precision

Most keywords apply to explicit and implicit

- *NODE, *ELEMENT, *SECTION, *MAT, ...
- easy to run a model with either method, but: carefully inspect input deck

Activating Implicit Analysis

Three types of analyses can be performed

- fully explicit (default)
- fully implicit
- switching: explicit - implicit, implicit - explicit (prescribed or automatic)

All keywords for implicit

*CONTROL_IMPLICIT_GENERAL	*CONTROL_IMPLICIT_SOLVER
*CONTROL_IMPLICIT_SOLUTION	*CONTROL_IMPLICIT_AUTO
*CONTROL_IMPLICIT_STABILIZATION	*CONTROL_IMPLICIT_DYNAMICS
*CONTROL_IMPLICIT_MODES	*CONTROL_IMPLICIT_EIGENVALUE
*CONTROL_IMPLICIT_BUCKLE	

Proper selection of LS-DYNA features

- not all features are available in implicit mode
- warning & error messages, feature substitution

Implicit Keywords

*CONTROL_IMPLICIT_GENERAL (required for implicit)

- activates implicit mode, explicit-implicit switching
- defines implicit time step size (standard LS-DYNA termination time is used too)

*CONTROL_IMPLICIT_SOLVER (optional)

- parameters for linear equation solver, which inverts stiffness matrix: [K]{x}={f}

*CONTROL_IMPLICIT_SOLUTION (optional)

- parameters for nonlinear equation solver (Newton-based methods)
- controls iterative equilibrium search, convergence
- "linear" analysis selected here (a special case where no iterations are performed)

*CONTROL_IMPLICIT_AUTO (optional)

- activates automatic time step control
- default is fixed time step size, error termination if any steps fail to converge

Implicit Keywords

*CONTROL_IMPLICIT_DYNAMICS (optional)

$$\mathbf{M}\Delta\mathbf{a}_{n+1} + \mathbf{K}\Delta\mathbf{u}_{n+1} = \mathbf{f}_{n+1}^{ext} - \mathbf{f}_{n}^{\text{int}} - \mathbf{M}\mathbf{a}_{n}$$

- include inertia terms
- problem “time” must now be real, physical time
- can improve convergence, especially when rigid body modes are present

*CONTROL_IMPLICIT_EIGENVALUE (optional)

- signals LS-DYNA to perform eigenvalue analysis, then stop
- number of eigenvalues/vectors, optional frequency shift
- great for debugging/model checking

*CONTROL_IMPLICIT_STABILIZATION (optional)

- Allows multi-step springback

➡ User‘s manual contains helpful notes on each input parameter, **Appendix M** gives survey of LS-DYNA/implicit features

Linear Static Analysis $\mathbf{Ku = R}$

Activate the implicit method

- ***CONTROL_IMPLICIT_GENERAL**: imflag = 1

Select a stepsize and termination time

- for static analysis, choice of time is arbitrary
- ***CONTROL_IMPLICIT_GENERAL**: dt0 = 1.0
- ***CONTROL_TERMINATION**: term = 1.0

nstep = term/dt0 = 1

Select linear solution method (no equilibrium iterations)

- ***CONTROL_IMPLICIT_SOLUTION**: nsolvr = 1

Select a linear element type

- shell # 18, 20, 21
- brick # 18

Use a double precision LS-DYNA executable

Element Formulations for Linear Analyses

Linear and nonlinear element formulations are different

- linear: integrate stress over undeformed geometry
- infinitesimal deformation eliminates some locking problems
- enhanced strain fields accurately represent linear elasticity

Brick Elements

- type 18: linear solid

$$\mathbf{f} = \int_{\Omega_0} \mathbf{B}^T \boldsymbol{\sigma} \, d\Omega$$

Shell Elements

- type 18: linear thin shell (Kirchoff)
- type 20: linear thick shell (Mindlin)
- type 21: linear enhanced shell (CQUAD4)

Boundary Constraints

Boundary conditions and rigid body modes

- static implicit simulation requires boundary constraints
- rigid body modes must be eliminated
  (otherwise stiffness matrix is singular / not invertible)
- apply translational constraints to three nodes

a - reference node, dx=dy=dz=0

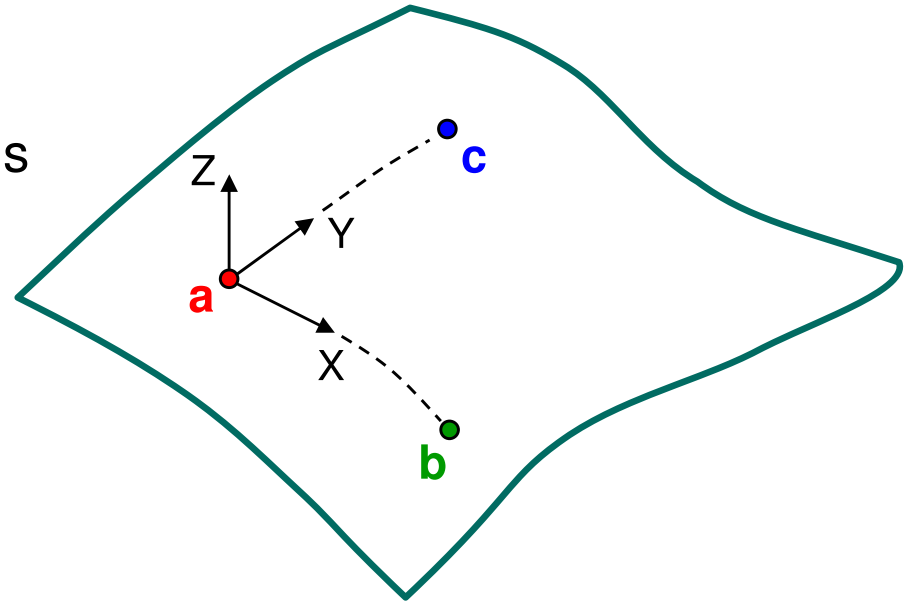
→ eliminates all translational modes

b - node along X-axis, dy=dz=0

→ eliminates rotations about y- and z-axis

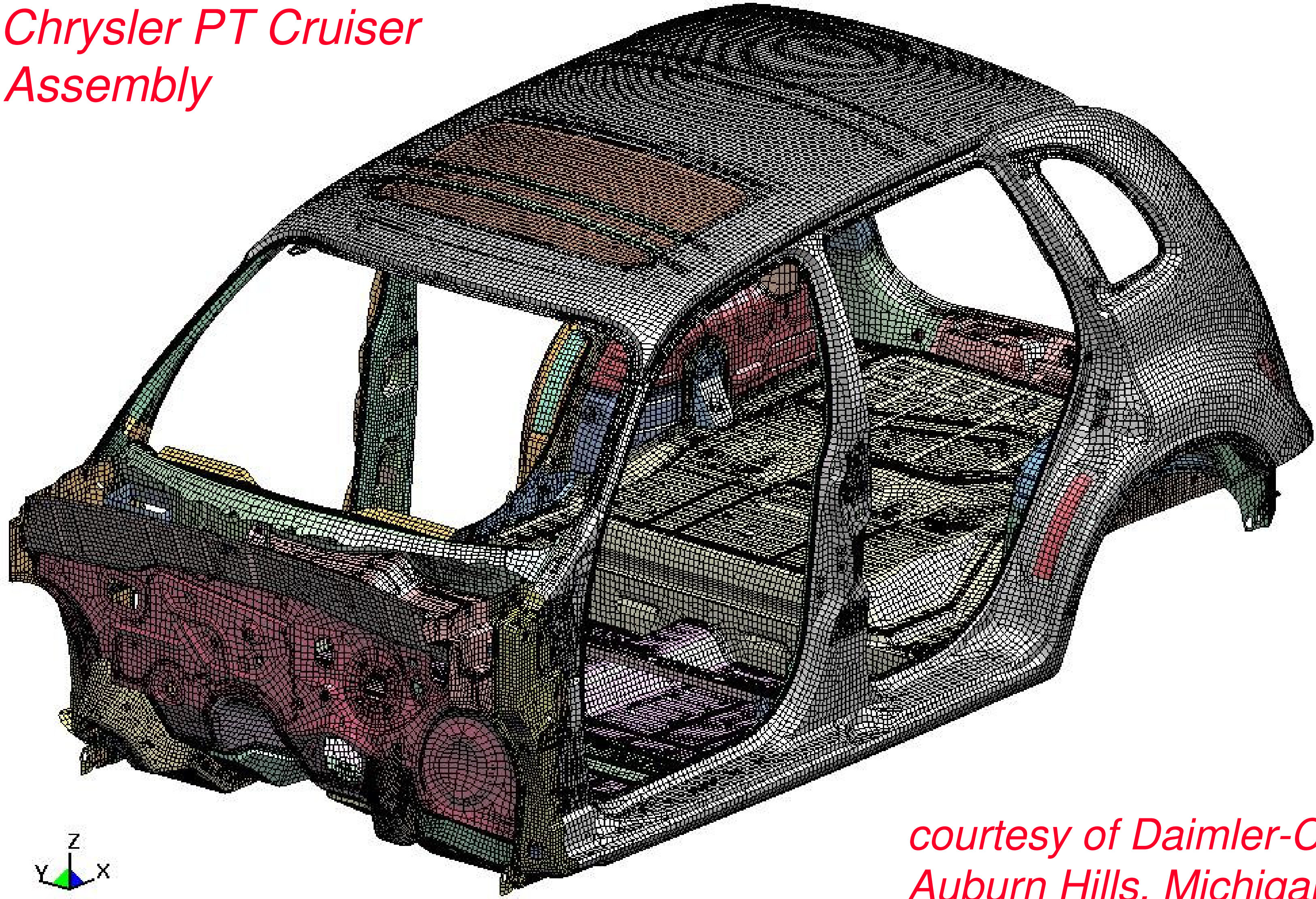
c - node along Y-axis, dz=0

→ eliminates rotation about x-axis



Example: Linear Static Analysis

2000 Chrysler PT Cruiser
Body Assembly

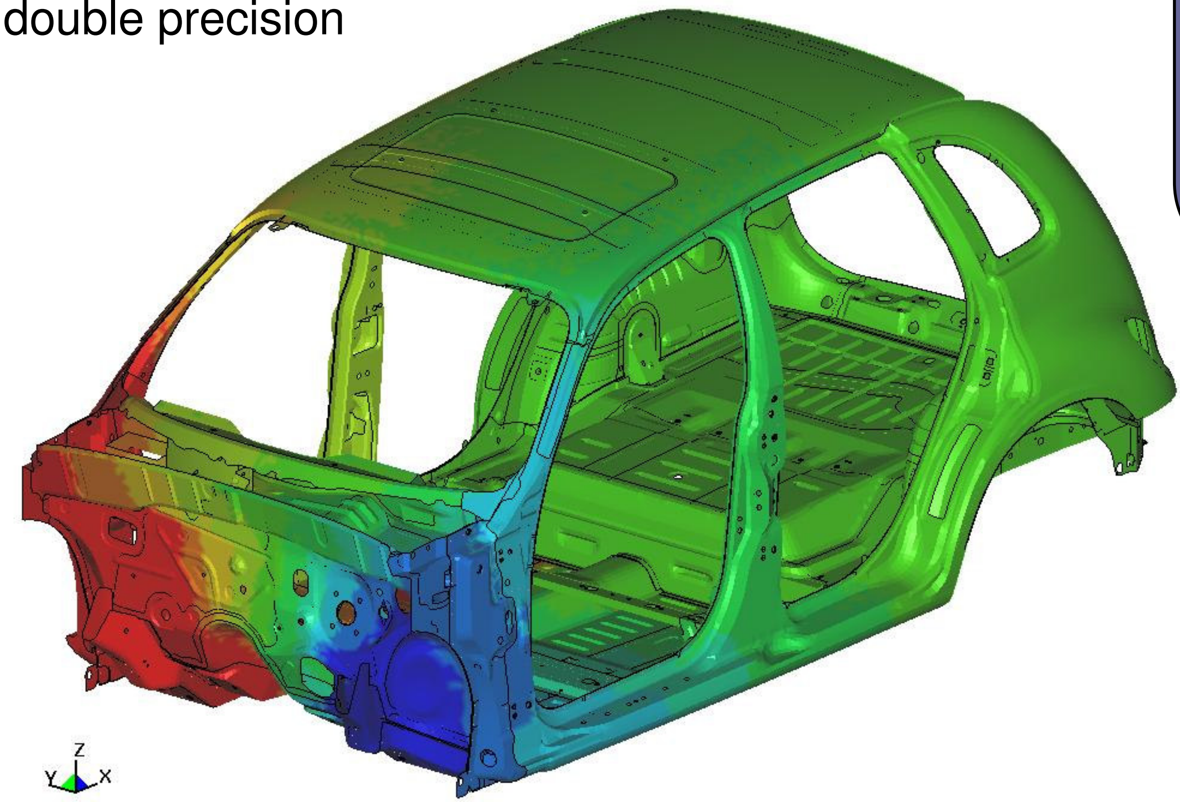


courtesy of Daimler-Chrysler
Auburn Hills, Michigan, USA

Example: Linear Static Analysis

Static Linear Torsion Analysis

- NSOLVR=1
- shell type 21
- double precision



model details

240,000 nodes
3,300 type 100 spotwelds
1,450,000 equations
memory=740m (~6 Gbyte)

SMP parallel performance

1 cpu: 753 sec
4 cpu: 485 sec

Attention: larger models demand 64-bit O/S to exceed 2 Gbyte memory limit

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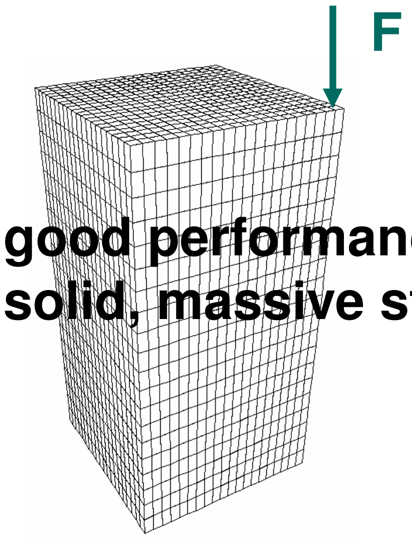
Linear Equation Solver

During each nonlinear iteration, the linear system $\hat{\mathbf{K}}\Delta\mathbf{u} = \hat{\mathbf{R}}$ is solved.

Direct Methods

LS-DYNA default

- gaussian elimination
- inexpensive backsolve (quasi-Newton)
- The sparse direct solver
- costly: CPU and memory
- robust and reliable



Iterative Methods

good performance for solid, massive structures

- iteration: improve approximate solution
- potentially low operation count
- convergence difficult for some problems
- promising future developments

Keyword ***CONTROL_IMPLICIT_SOLVER**

Direct Solvers

A sparse, direct linear equation solver is used by default (LSOLVR=4)

- serial or SMP parallel execution
- automatic out-of-core mode if insufficient memory available for incore
- double precision version also available (LSOLVR=5)
  - improved convergence for a few models
  - 2x memory penalty
  - better to use a double precision version of LS-DYNA
- BCSLIB-EXT solver from Boeing also available (LSOLVR=6)
  - double precision only
  - best for very large models (excellent out-of-core performance)

All sparse direct solvers execute in three phases

- symbolic factorization
- numeric factorization
- forward elimination / back substitution

Iterative Solvers

LS-DYNA offers six iterative linear equation solvers

- LSOLVR = 10: “best” iterative solver (currently activates #16)
  LSOLVR = 11: Conjugate Gradient method
  LSOLVR = 12: CG with Jacobi preconditioning
  LSOLVR = 13: CG with Incomplete Choleski preconditioning
  LSOLVR = 14: Lanczos method
  LSOLVR = 15: Lanczos with Jacobi preconditioning
  LSOLVR = 16: Lanczos with Incomplete Choleski preconditioning

All iterative solvers use the sparse matrix storage scheme

- eliminates all zero entries inside bandwidth
- minimizes total storage requirement
- Boeing Harwell format for portability

Dynamic Implicit Analysis

$$\mathbf{M}\Delta\mathbf{a}_{n+1} + \mathbf{K}\Delta\mathbf{u}_{n+1} = \mathbf{f}_{n+1}^{ext} - \mathbf{f}_{n}^{\text{int}} - \mathbf{M}\mathbf{a}_{n}$$

Newmark Method relates displacement, velocity, acceleration

$$\mathbf{u}_{n+1} = \mathbf{u}_n + \mathbf{v}_n \Delta t + \left[\left(\tfrac{1}{2} - \beta\right)\mathbf{a}_n + \beta\,\mathbf{a}_{n+1}\right]\Delta t^2$$

$$\mathbf{v}_{n+1} = \mathbf{v}_n + \left[(1-\gamma)\mathbf{a}_n + \gamma\,\mathbf{a}_{n+1}\right]\Delta t$$

$\beta = 0, \ \gamma = 1/2$	: explicit central difference method
$\beta = 1/4, \ \gamma = 1/2$	: implicit undamped trapezoidal rule
$\gamma > 1/2$	: numerical damping

LS-DYNA default

- convergence may be possible with large DT
- small DT may be needed to resolve high frequency response
- stabilizing effect to nonlinear equilibrium iterations
- rigid body modes OK! (mass terms eliminate singularity)

$$\hat{\mathbf{K}} = \mathbf{K} + \left(\frac{1}{\beta\,\Delta t^2}\right)\mathbf{M}$$

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Activating Dynamic Implicit Analysis

Activating Dynamic Analysis

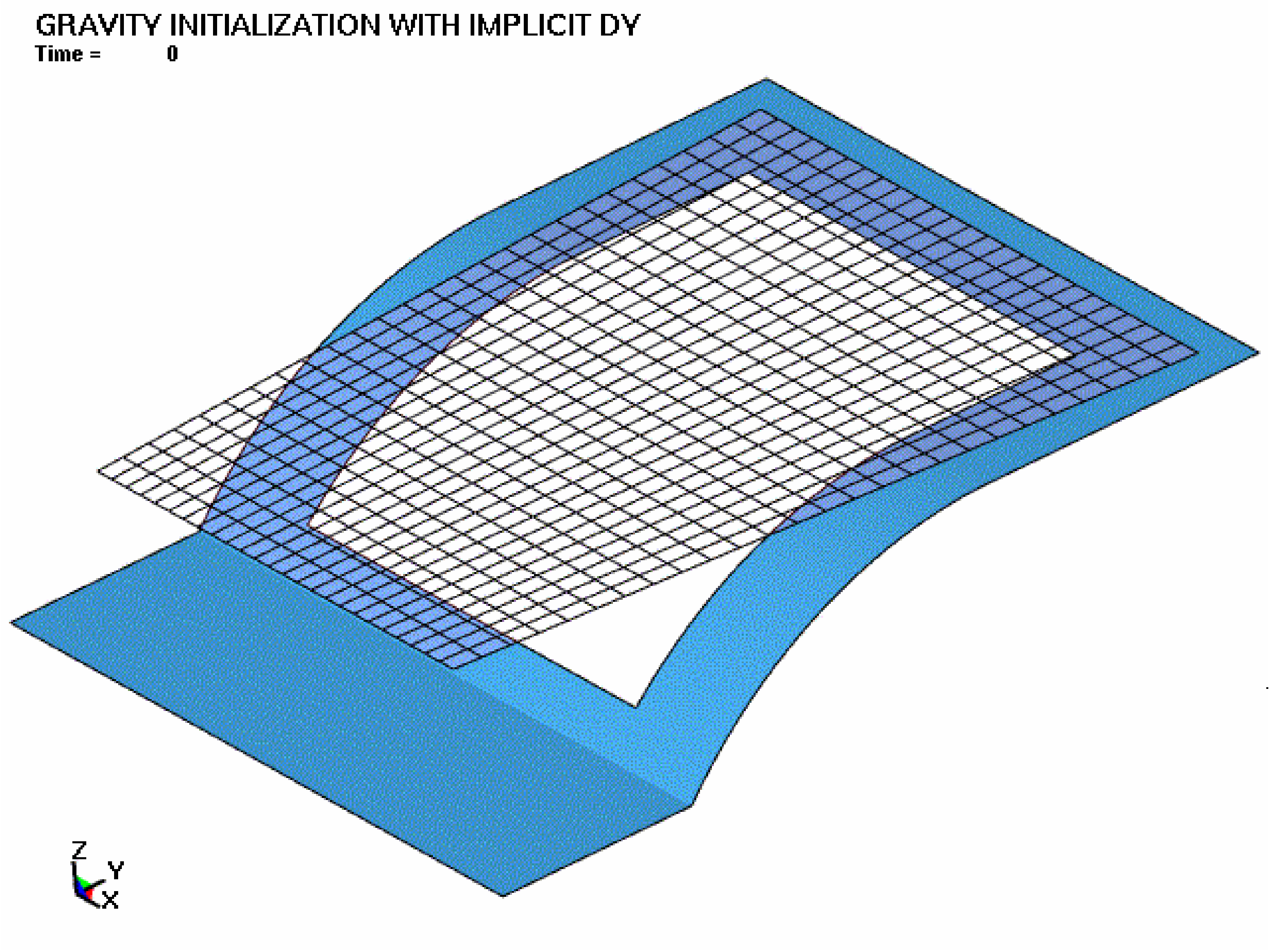
```
*CONTROL_IMPLICIT_DYNAMIC
$     imass      gamma       beta
          1          0          0
```

Implicit Dynamic Analysis may be linear or nonlinear

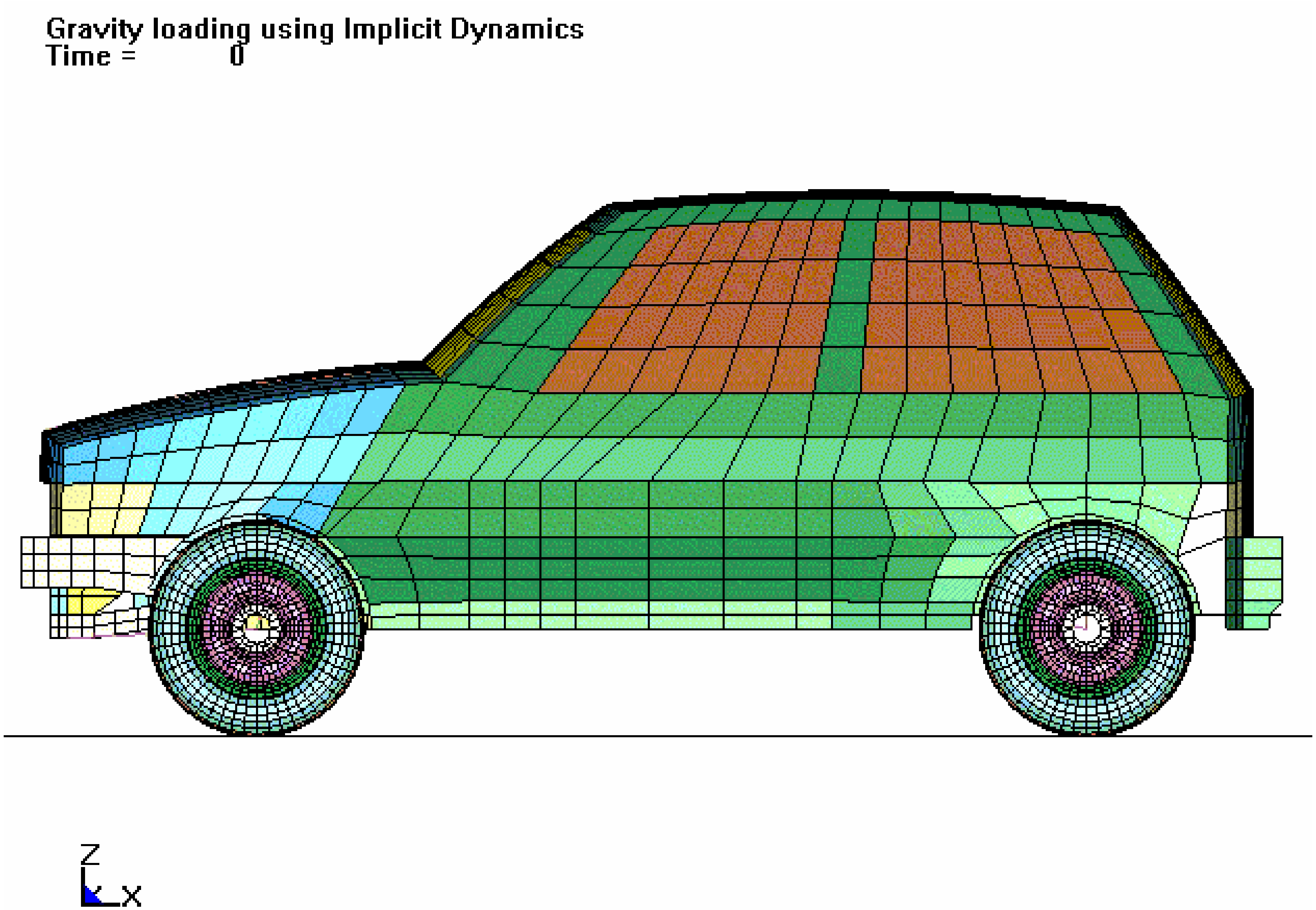
- inertia terms are simply added to stiffness matrix and residual vector
- very efficient when only one stiffness matrix factorization is performed
  - earthquake response analysis: long periods of nearly linear behavior
  - same stiffness matrix used for many nonlinear steps
- if time step size changes, a new stiffness will automatically be formed

$$\hat{\mathbf{K}} = \mathbf{K} + \left(\frac{1}{\beta \, \Delta t^2} \right) \mathbf{M}$$

Example: Sheet Metal Gravity Loading



Example: Car gravity loading



Eigenvalue Analysis

Compute Natural Frequencies and Mode Shapes

- linear analysis
- infinitesimal deformation (magnified for display)

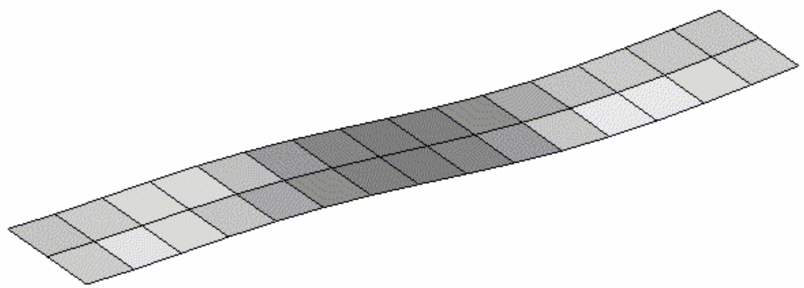
$$(\mathbf{K} - \lambda \mathbf{M})\,\boldsymbol{\varphi} = 0$$

Accuracy Requires Special Considerations

- linear elements (type 18, 20)
- double precision executable

Applications

- frequency analysis
- model integrity check
- extract modes for modal analysis



Activating Eigenvalue Analysis

Required Input Parameters

- non-zero termination time

  ***CONTROL_TERMINATION** `term=1.0`

- implicit analysis

  ***CONTROL_IMPLICIT_GENERAL** `isolvr=1, dt0=1.0`

- number of eigenvalues

  ***CONTROL_IMPLICIT_EIGENVALUE** `neigv=30`

Eigenvalue analysis with an existing implicit input deck

- just add one keyword, one input parameter:

```
*CONTROL_IMPLICIT_EIGENVALUE
$     neigv     center
         30        0.0
```

- LS-DYNA computes 30 lowest modes, terminates

Eigenvalue Input / Output

Input Options

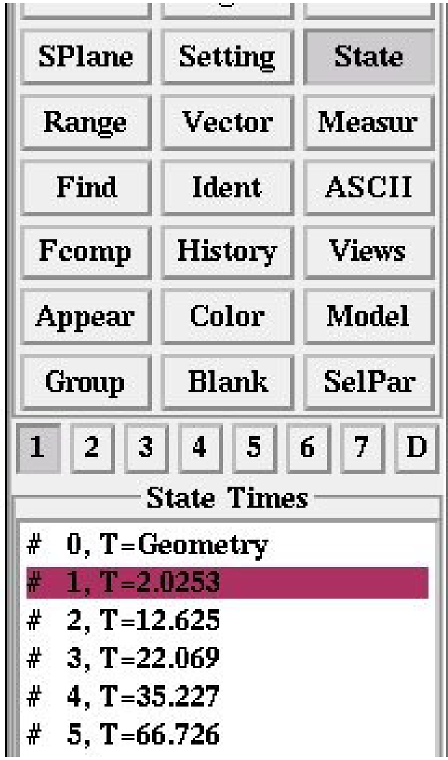
- number of eigenvalues/modes
- center frequency, frequency range
- eigenvalue extraction method: Lanczos eigensolver (default)

New output databases

- **d3eigv**: - binary plot database similar to d3plot
  - each state shows one mode shape
  - “State times” give circular frequencies f →
- **eigout**: - ASCII text file
  - summary of frequencies found

λ $\quad\quad$ $\omega = \sqrt{\lambda}$ $\quad\quad$ $f = \omega / 2\pi$ $\quad\quad$ $T = 1/f$

MODE	EIGENVALUE	RADIANS	CYCLES	PERIOD
1	1.619382E+02	1.272549E+01	2.025325E+00	4.937478E-01
2	6.292547E+03	7.932558E+01	1.262506E+01	7.920756E-02
3	1.922690E+04	1.386611E+02	2.206860E+01	4.531325E-02



Mode Extraction

*CONTROL_IMPLICIT_MODES

Modal Analysis

- approximate structural deformation using a set of modes
- modal amplitudes become the unknowns
- greatly reduced problem size
- superposition principle assumes linearity

Flexible Rigid Bodies

- large rigid body motion + superimposed modal deformation
- apply to a subset of parts, treat others as fully nonlinear

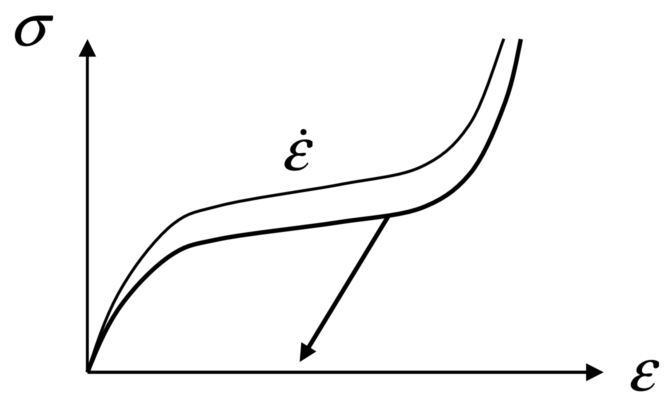
Analysis Procedure

1. compute modes for subset of parts (d3eigv, d3mode in v970)
2. rigidize, merge these parts
3. define *PART_MODES for master part
4. perform explicit transient dynamic analysis

Nonlinear Implicit Analysis

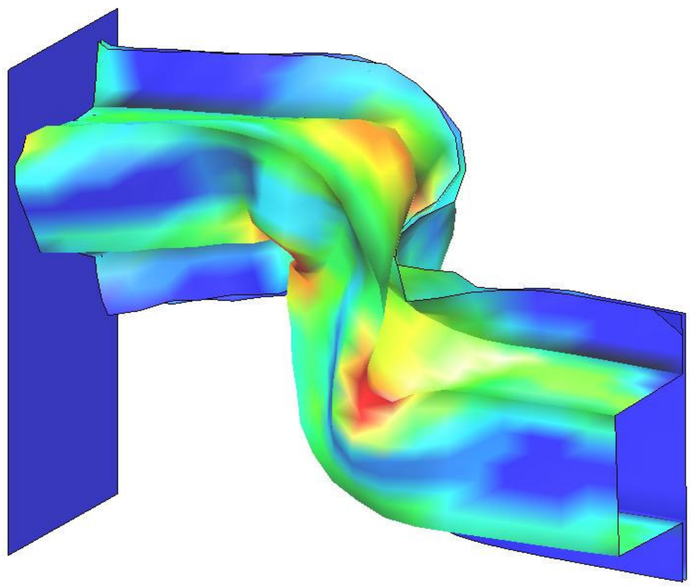
Material Nonlinearity

- plasticity, damage, failure
- rate dependence
- slope of stress-strain curve gives stiffness, should usually be monotonic



Geometric Nonlinearity

- large displacement, large rotation



Contact Nonlinearity

- normal force is sharply discontinuous
- frictional effects elastic-perfectly-plastic

Nonlinear Implicit Analysis

Implicit governing equations contain two problems to solve

$$\mathbf{M}\Delta\mathbf{a}_{n+1} + \mathbf{K}\Delta\mathbf{u}_{n+1} = \mathbf{f}^{ext}_{n+1} - \mathbf{f}^{\text{int}}_{n} - \mathbf{M}\mathbf{a}_{n}$$

Nonlinear Equilibrium Problem: *CONTROL_IMPLICIT_SOLUTION

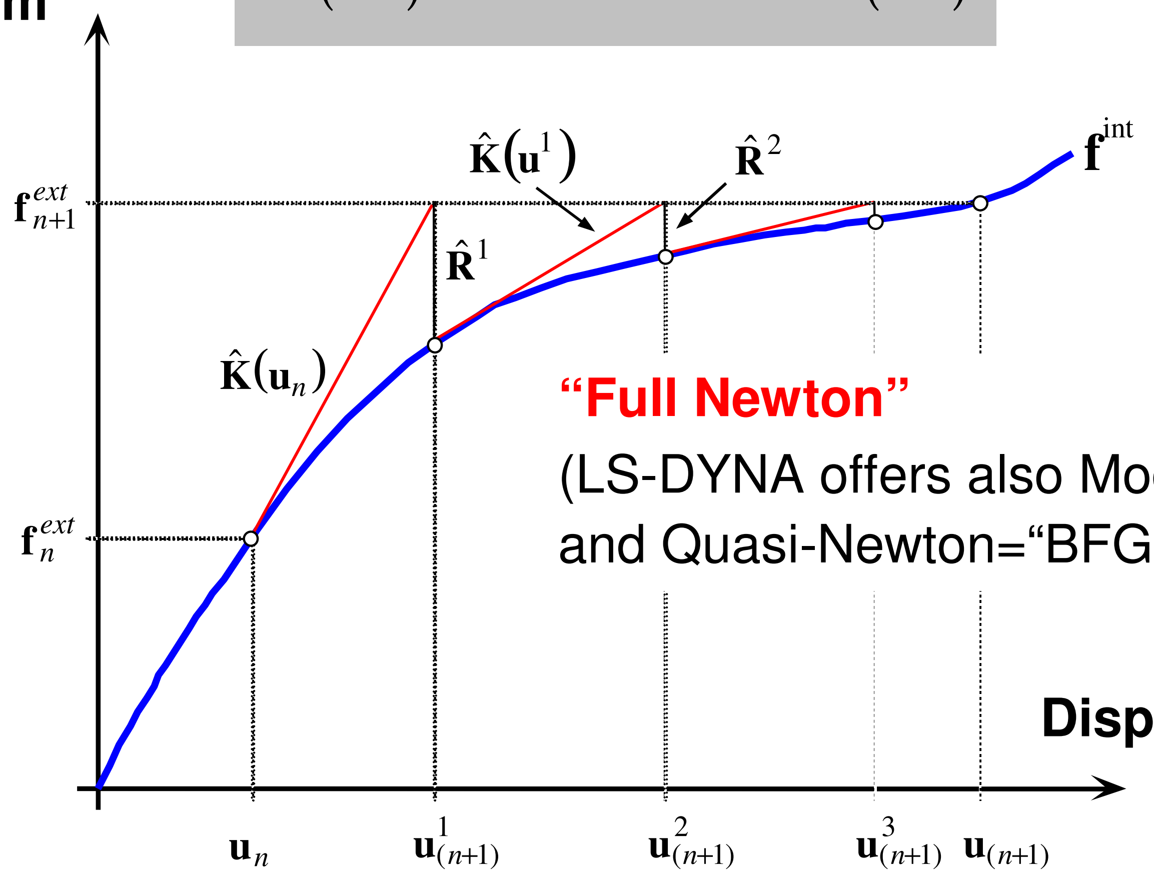
- find displacements **u** which satisfy equilibrium **f**ext=**f**int
- both **K**, **f**ext and **f**int can be nonlinear functions of ***u***
- iterative search employed using Newton-based method
- interactive switch "<ctrl-c> nlprint" toggles diagnostic output

Linear Algebra Problem: *CONTROL_IMPLICIT_SOLVER

- solve system of linear algebraic equations
- must solve during every nonlinear iteration
- great CPU and memory cost
- interactive switch "<ctrl-c> lprint" toggles diagnostic output

Nonlinear Equation Solver - Newton Method

$$\hat{\mathbf{K}}\left(\mathbf{u}^{(i)}\right)\Delta\mathbf{u} = \hat{\mathbf{R}}^{(i)} = \mathbf{f}^{ext} - \mathbf{f}^{\text{int}}\left(\mathbf{u}^{(i)}\right)$$



"Full Newton"

(LS-DYNA offers also Modified Newton and Quasi-Newton="BFGS")

Equilibrium is reached when iterations converge: $\left\|\Delta\mathbf{u}\right\| \to 0\,,\ \left\|\hat{\mathbf{R}}^{(i)}\right\| \to 0$

Input Parameters for Nonlinear Solver

NSOLVR: nonlinear solution method

- =1: linear approximation (no equilibrium iterations)
- =2: BFGS quasi-Newton method (DEFAULT)

ILIMIT: equilibrium iteration limit before re-evaluating $\hat{\mathbf{K}}$

- =1: new $\hat{\mathbf{K}}$ each iteration (“**Full Newton**" method)
- =11: use cheap BFGS update for 11 iterations, reform if not yet converged

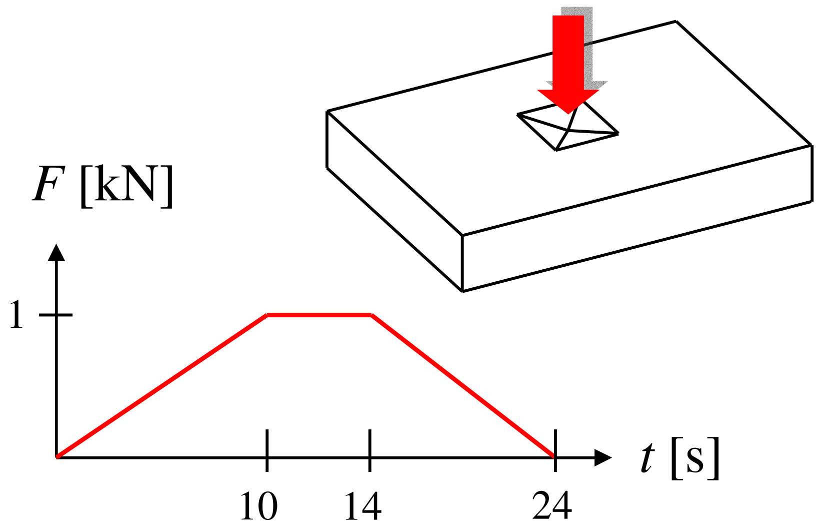
MAXREF: maximum reformation count before abandoning step

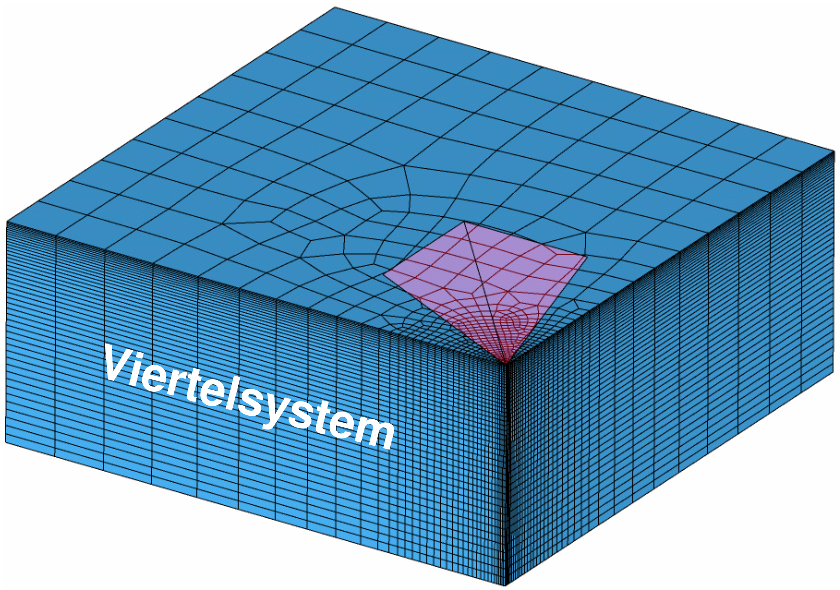
- if AUTO is active, dt will be reduced and step will be re-tried, so MAXREF can be smaller (~5)
- if AUTO not active, error termination occurs when MAXREF is reached so MAXREF should be larger (~15, default)

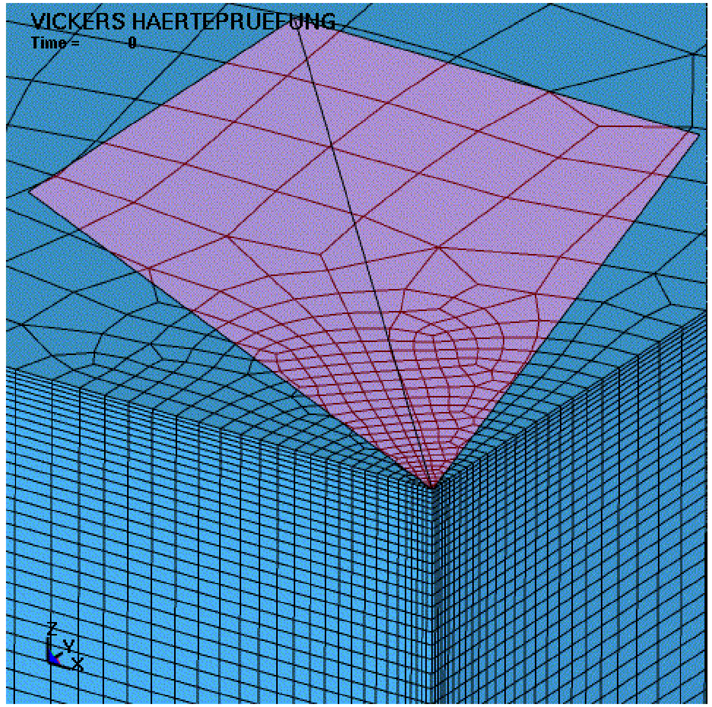
DCTOL, ECTOL: convergence tolerances

- use NLPRINT=1 or "<ctrl-c> nlprint" to monitor progress of iterations

Example: Vickers Hardness Test







implicit

1 cpu: 4 h

memory=140m (1.1 GB)

explicit

1 cpu: 270000 h (2.4E10 cycles)

Automatic Time Step Control

Automatic time step control adjusts stepsize during the simulation

- very persistent, reliable

***CONTROL_IMPLICIT_AUTO**

After successful steps

- compare iteration count to target value ITEOPT
- increase/decrease size of next step if difference exceeds window ITEWIN

After failed steps

- decrease step size
- back up, repeat failed step with new DT

Exponential algorithm for adjusting step size

- increase stepsize by 1/5 decade until DTMAX is reached
- decrease stepsize by 1/3 decade until DTMIN is reached
- error termination if convergence fails when DT=DTMIN

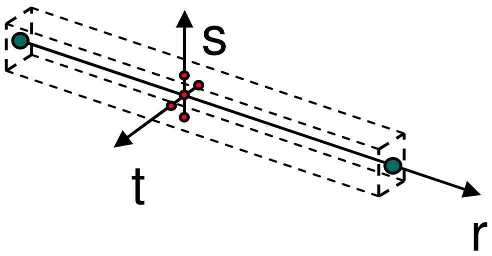
Implicit Capabilities: Element Types

Brick Elements: 1, 2, 3, 4, 10, 15, 16, 18

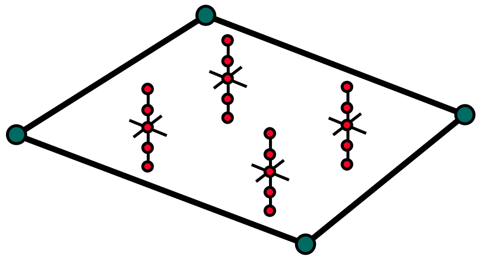
Beam (and 2D Shell) Elements: 1, 2, 3, 4, 5, 6, 7, 8, 9

Shell (and 2D Solid) Elements: 2, 4, 6, 10, 12, 13, 15, 16, 17, 18, 20, 21

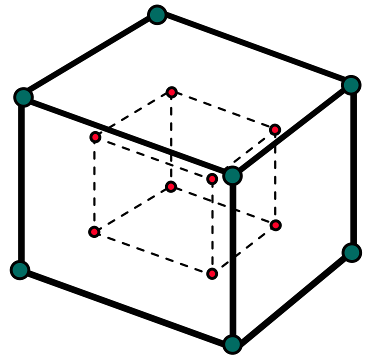
→ ***recommended*** **elements for implicit, e.g.**



Hughes-Liu:
type **1** (default)



fully integrated:
type **16** (not default!)



fully integrated S/R:
type **2** (not default!)

Alternate shell element formulations are substituted if requested elements are not available for implicit

Implicit Capabilities: Material Models

- stiffness matrix terms require extra evaluation of $\delta\sigma/\delta\varepsilon$
- some material models only available for selected element formulations

3D Solid Elements

- 1-7, 11, 12, 13, 14-17, 18, 19, 20, 21-23, 24, 26, 27, 30, 31, 33, 35, 36, 38, 41-50, 51-53, 57, 59, 60-62, 63, 64, 65, 70, 72, 73, 75-80, 83-85, 87-89, 91, 92, 96, 98, 100, 102, 103, 104, 105, 106, 107, 109-112, 115, 124, 126-129, 141-145, 161, 177, 178, 192, 193

Shell Elements

- 1-4, 6, 9, 18, 20, 21-23, 24, 27, 32, 36, 37, 41-50, 54, 55, 60, 76, 77, 91, 92, 98, 99, 103, 104, 106, 107, 116-118, 123

Beam Elements

- 1, 3, 4, 6, 9, 18, 20, 24, 41-50, 100

2D Solid Elements

- 1-7, 9, 12, 13, 18, 20, 24, 26, 41-50, 57, 63, 103, 104, 106, 107

Implicit Capabilities: Contact Interfaces

Several contact interfaces are available for implicit analysis

- *CONTACT_SURFACE_TO_SURFACE
- *CONTACT_NODES_TO_SURFACE
- *CONTACT_ONE_WAY_SURFACE_TO_SURFACE
- *CONTACT_FORMING_… (three variations)
- *CONTACT_AUTOMATIC_… (three variations)
- *CONTACT_TIED, …TIED_OFFSET
- *CONTACT_AUTOMATIC_SINGLE_SURFACE

All implicit contact interfaces use the penalty method, except TIED

Shooting node logic is automatically disabled for implicit

- SNLOG=1 on optional contact interface card "B"

Oriented normal vectors are recommended

Automatic contact types can fail due to large implicit stepsize

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Nonlinear Convergence Problems

Convergence trouble is the most common problem

Error messages displayed by LS-DYNA, e.g.

- **iteration limit reached**

  displacement and energy tolerances were not satisfied, abandon step
- **divergence**

  out-of-balance force **R** is growing, reform **K** and continue iterations
- **negative eigenvalues**

  error from linear equation solver while computing $\mathbf{K}^{-1}$

Procedures for solving convergence problems

- determine reason for termination (examine error messages)
- activate print flags to get more information
- view deformed geometry during iteration process using "d3iter" database
- carefully inspect input deck
- see user’s manual: Appendix M

Current and Future Developments

MPP Implicit is nearing completion with all capabilities implemented

- Implicit simulation (statics and dynamics)
- Springback
- Vibration and Buckling analysis → **Version 971**
- Constraint and Attachment modes

Transition from dynamic to static

- e.g. gravity loading, roof crush

Implementation of still missing features, e.g.

- e.g. consistent tangent stiffness for more materials
- elements, e.g. type 13 tetrahedron for bulk forming
- contact types
- seatbelts
- airbags: fabric materials, inflator models, soft=2 - contact