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A FINITE ELEMENT APPROACH FOR LARGE MOTION DYNAMIC ANALYSIS OF MULTIBODY STRUCTURES IN SPACE

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ABSTRACT

A three-dimensional finite element formulation for modeling the transient dynamics of constrained multibody space structures with truss-like configurations is presented. Convected coordinate systems are used to define rigid-body motion of individual elements in the system. These systems are located at one end of each element and are oriented such that one axis passes through the other end of the element. Deformation of each element, relative to its convected coordinate system, is defined by cubic flexural shape functions as used in finite element methods of structural analysis. The formulation is oriented toward joint dominated structures and places the generalized coordinates at the joint. A transformation matrix is derived to integrate joint degree-of-freedom into the equations of motion of the element. Based on the derivation, a general-purpose code LATDYN (Large Angle Transient DYNamics) has been developed. Two examples are presented to illustrate the application of the code. For the spin-up of a flexible beam, results are compared with existing solutions available in the literature. For the deployment of one bay of a deployable space truss (the "Minimast"), results are verified by the geometric knowledge of the system and converged solution of a successively refined model.

LATDYN

Large Angle Transient DYNamics

(Finite-Element-Based)

A NASA Facility for <u>Research</u>

in

Applications and Analysis Techniques

for Space Structure Dynamics

Presented by

Che-Wei Chang

COMTEK

TALK OUTLINE

* Motivation
* Capability
* Theory
* Modelling
* Present LATDYN (verifications)
* Future LATDYN
* Conclusions

CAPABILITIES

* Three-Dimensional
* Deformable Bodies
* Multi-Connection Joints
* Large Angular Motion
* Variable Constraints
* Impacts & Joint-Lock
* Experimental Data
* User's Control Strategy

BACKGROUND THEORY

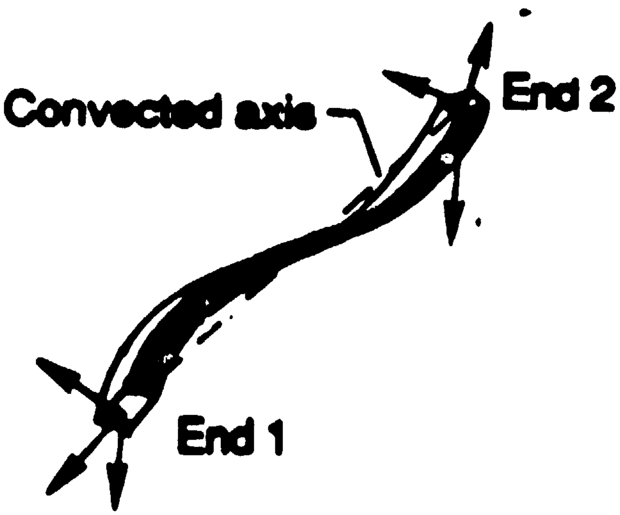
1. Corotational Axes
   (convected system)

2. F-E Connectivity through
   Joint Kinematics

3. Numerical Integrations

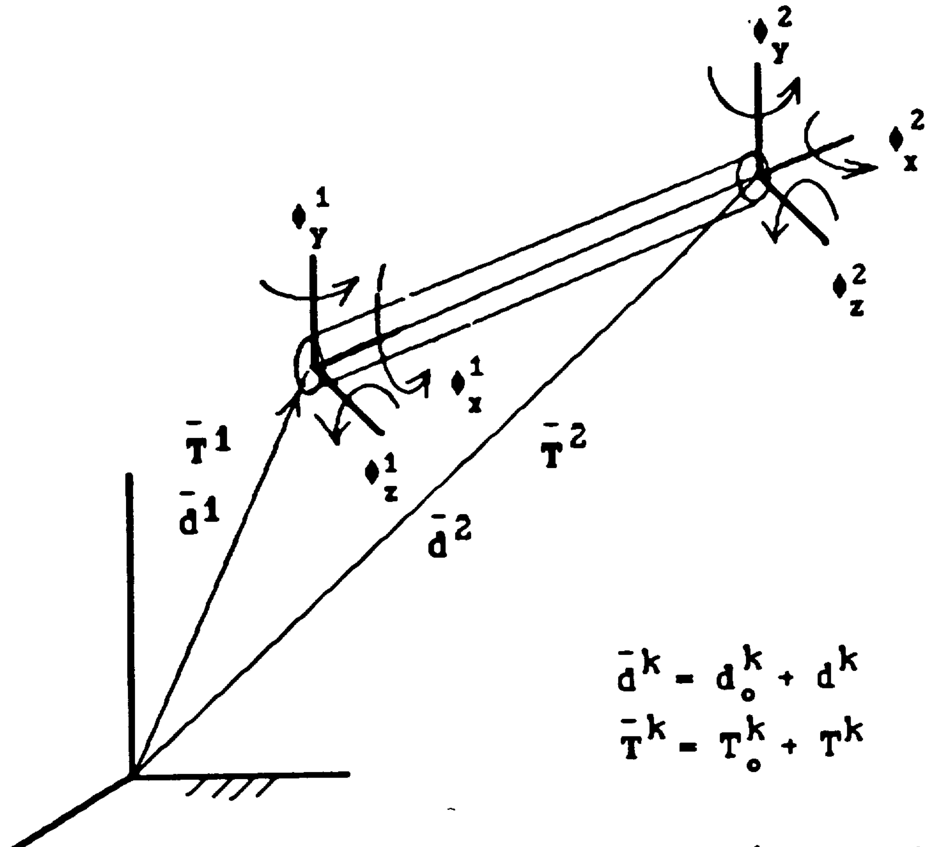
DEFORMED FINITE ELEMENT AND ELEMENT COORDINATE SYSTEMS

Element coordinates move
with cross-section



Deformations are measured from convected axes

Deformation : u



$$\bar{d}^k = d_o^k + d^k \qquad ; k = 1 \text{ or } 2$$
$$\bar{T}^k = T_o^k + T^k$$

$$\Phi = [\phi_x^1, \phi_y^1, \phi_z^1, \phi_x^2, \phi_y^2, \phi_z^2, u_x^1, u_y^1, u_z^1, u_x^2, u_y^2, u_z^2]^T$$

$$\boxed{\mathbf{u} = \mathbf{N}\,\Phi}$$

$$\mathbf{u} = [u_x, u_y, u_z]^T$$

$$\boxed{\Phi = \Phi(d, T)}$$

$$\mathbf{d} = [\mathbf{d}^{1^T}, \mathbf{d}^{2^T}]^T$$
$$\mathbf{T} = \mathbf{T}(\theta^1, \theta^2)$$

Internal Force

because

$$\varepsilon = \mathbf{D}\,\Phi \qquad \& \qquad \sigma = \mathbf{E}\,\varepsilon$$

$\therefore$

$$\sigma = \mathbf{E}\,\mathbf{D}\,\Phi$$

$$\delta\varepsilon = \mathbf{D}\,\delta\Phi = \mathbf{DB}\,\delta q$$

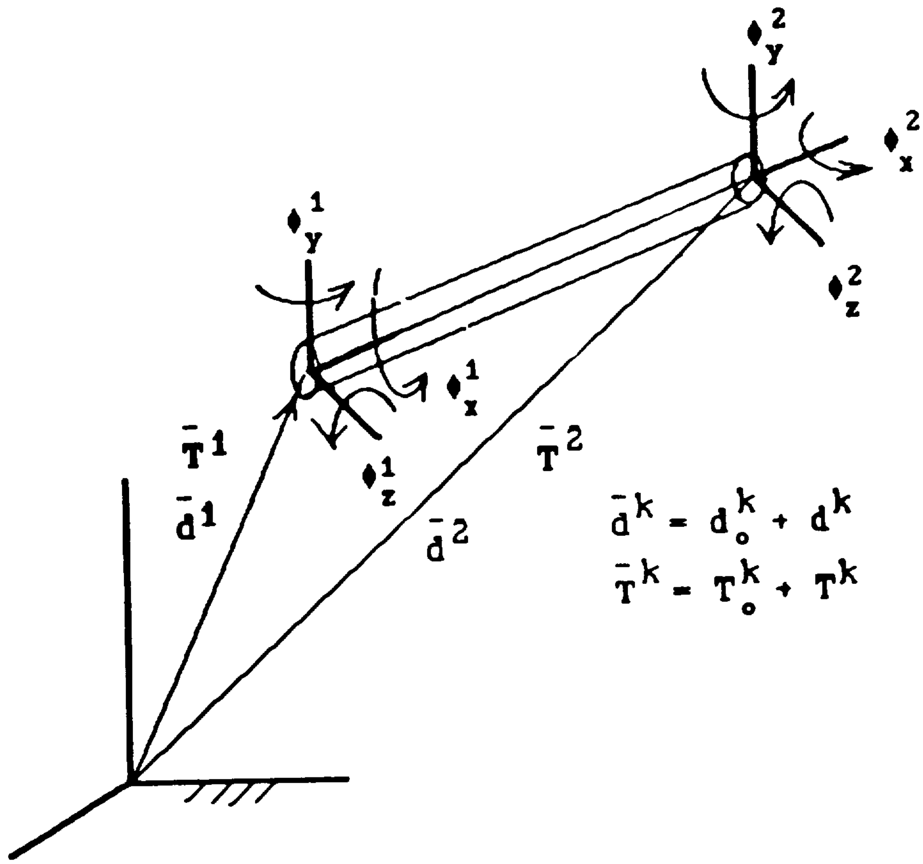
virtual work done by internal force

$$\delta W = -\delta U$$

$$= -\int_{dv} \delta\varepsilon^T \sigma \; dv$$

$$= \delta q^T \{-\int_{dv} (\mathbf{DB})^T \mathbf{D}\Phi \, dv\}$$

Total displacement $\bar{\mathbf{u}}$



$\bar{d}^k = d_o^k + d^k$; $k = 1$ or 2

$\bar{T}^k = T_o^k + T^k$

$$\bar{\mathbf{u}} = \bar{\mathbf{d}}^1 + \mathbf{T}_c\,\mathbf{u}$$

$$\delta\bar{\mathbf{u}} = \mathbf{C}\;\delta\mathbf{q}$$

$$\dot{\bar{\mathbf{u}}} = \mathbf{C}\;\dot{\mathbf{q}}$$

$$\ddot{\bar{\mathbf{u}}} = \mathbf{C}\,\ddot{\mathbf{q}} + \dot{\mathbf{C}}\;\dot{\mathbf{q}}$$

C-4

Inertia

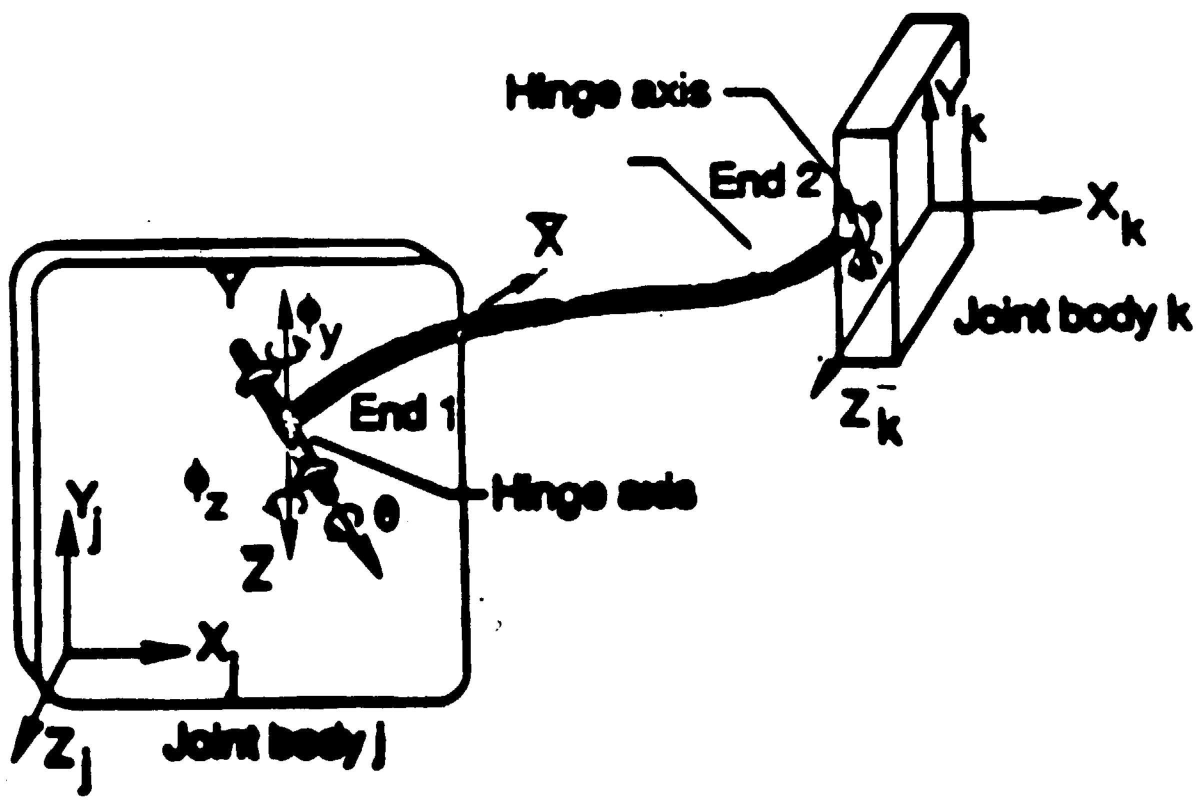
virtual work done by inertia force

$$\delta W = \int_{dv} \{\delta \bar{u}^T (-\rho \ddot{\bar{u}})\} dv$$

$$= \delta q^T \{-(\int_{dv} \rho\, C^T C \; dv)\ddot{q}\}$$

$$+ \delta q^T \{-(\int_{dv} \rho\, C^T \dot{C} \; dv)\dot{q}\}$$

TYPICAL INTERCONNECTION OF TWO JOINT BODIES THROUGH FLEXIBLE BEAM

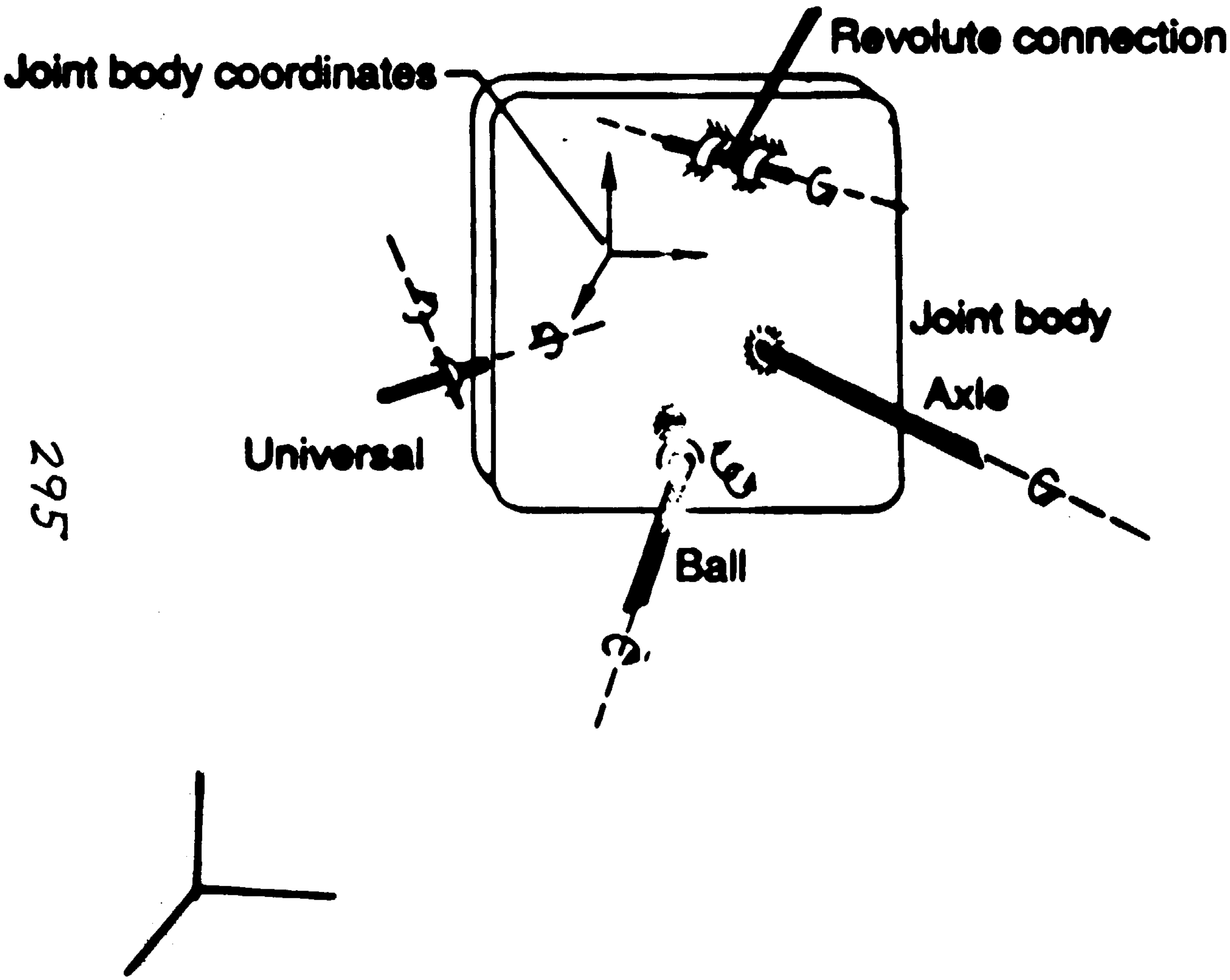


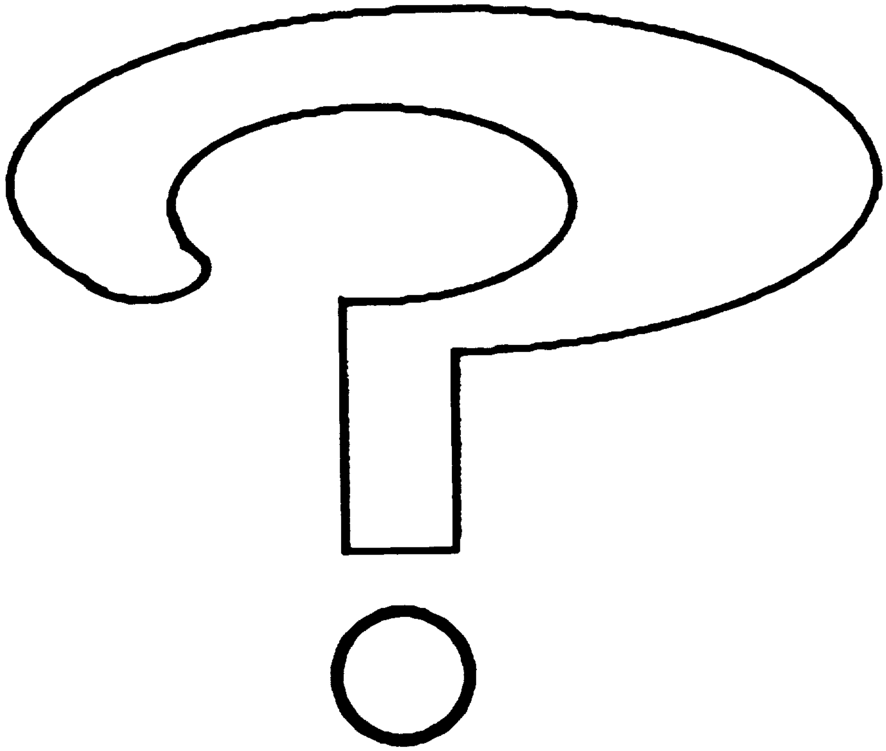
Element EQ's of Motion

in terms of nodal disp.

$$M\ddot{q} = F^{E} + F^{I} + g$$

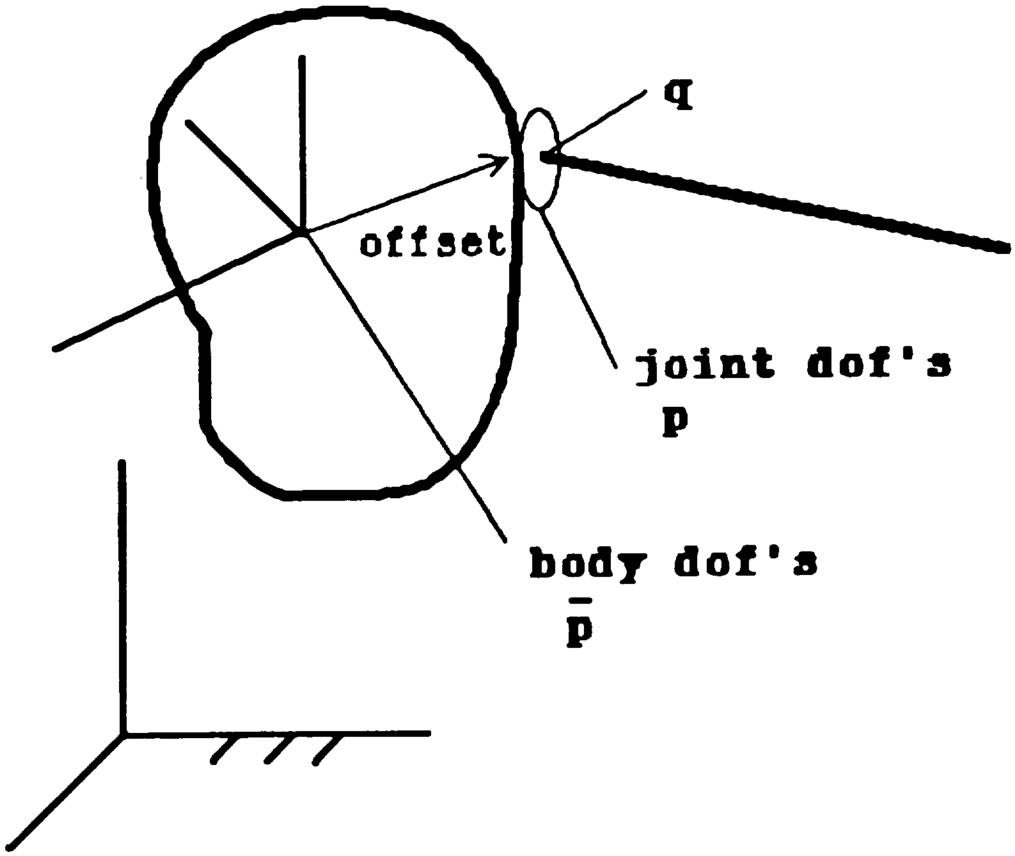
GENERIC JOINT BODY WITH VARIOUS TYPES OF HINGE CONNECTIONS





$$M\ddot{q} = F^{E} + F^{I} + g$$

Joint Kinematics



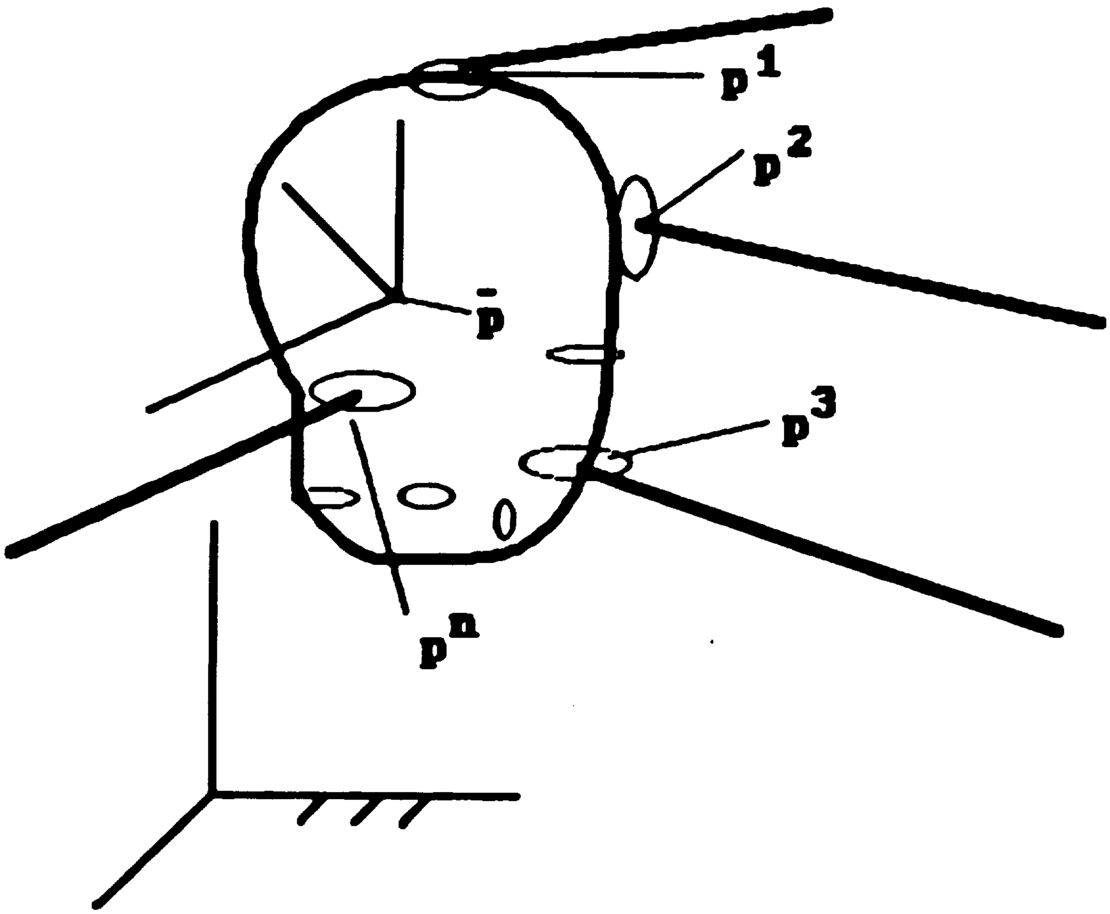
$$q = q(\bar{p}, p) = q(\bar{q})$$

$$\delta q = H\,\delta\bar{q}$$

$$\dot{q} = H\,\dot{\bar{q}}$$

$$\ddot{q} = H\,\ddot{\bar{q}} + \dot{H}\,\dot{\bar{q}}$$

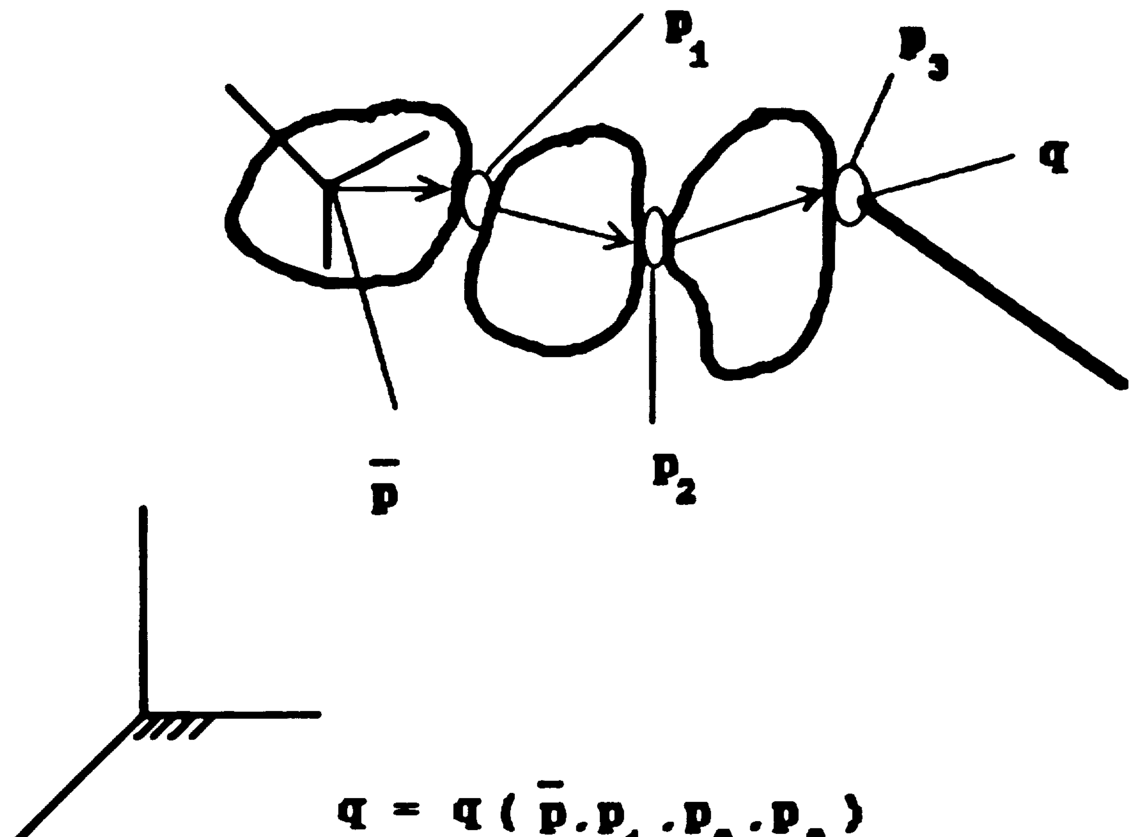
Multi-Joint Body



generalized coords.

$$\bar{q} = [\bar{p}^T, p^{1T}, p^{2T}, \ldots\ldots, p^{nT}]^T$$

Rigid Chain



$$q = q(\bar{p}, p_1, p_2, p_3)$$

generalized coord.

$$\bar{q} = [\bar{p}^T, \ p_1^T \ , \ p_2^T \ , \ p_3^T \ ]^T$$

<u>Generalized Coordinates</u>

at each joint body:

3 translational disp.

3 orientational disp.

\+ No. of relative(joint) d-o-f's

System EQ's of Motion

in terms of joint body
and joint dof's

$$\bar{M}\ddot{\bar{q}} = \bar{F}^{E} + \bar{F}^{I} + \bar{g}$$

Equations of Motion and Their Numerical Integration

At nth time step,

$$M^n a^n + f^n + g^n = F^n$$

Newmark-Beta Integrator at kth iteration:

$$a_k^n = a_{k-1}^n + \left[M_{k-1}^n + \frac{h}{2}G_{k-1}^n + \beta h^2 K_{k-1}^n\right]^{-1} R_k^n$$:Update Accelerations

$$R_k^n = \text{iterative residual} = F^n - f_{k-1}^n - M_{k-1}^n a_{k-1}^n$$

$$V_k^n = V^{n-1} + \left(\frac{h}{2}\right)\left(a^{n-1} + a_k^n\right)$$:Update Velocities

Equations of Motion and Their Numerical Integration (cont'd)

Split into translational and rotational d.o.f.

Translational displacements are

$$d_k^n = d^{n-1} + hv^{n-1} + \left(\tfrac{1}{2} - \beta\right) h^2 a^{n-1} + \beta h^2 a_k^n \qquad \text{:Update Translational d.o.f.}$$

Rotational motions are given by transformation matrix:

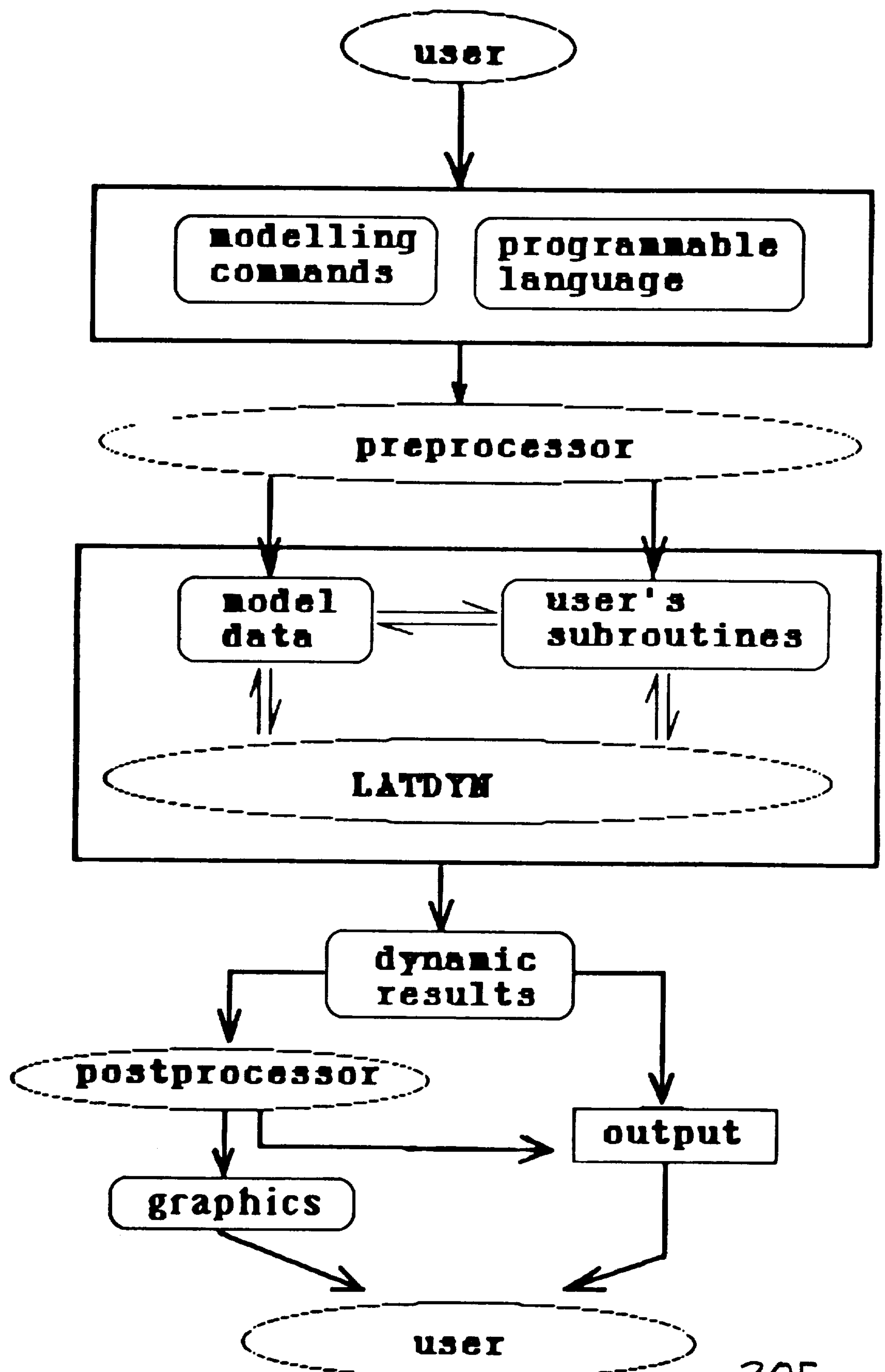
$$T_k^n = \left[1 + h\overline{\omega}_k^n + \tfrac{1}{2} h \left(\overline{\omega}_k^n\right)^2\right] T^{n-1} \qquad \text{:Update hinge body transformation}$$

$$\bar{\omega}_k^n = \omega_k^n + \omega^{n-1}$$

Modelling Techniques

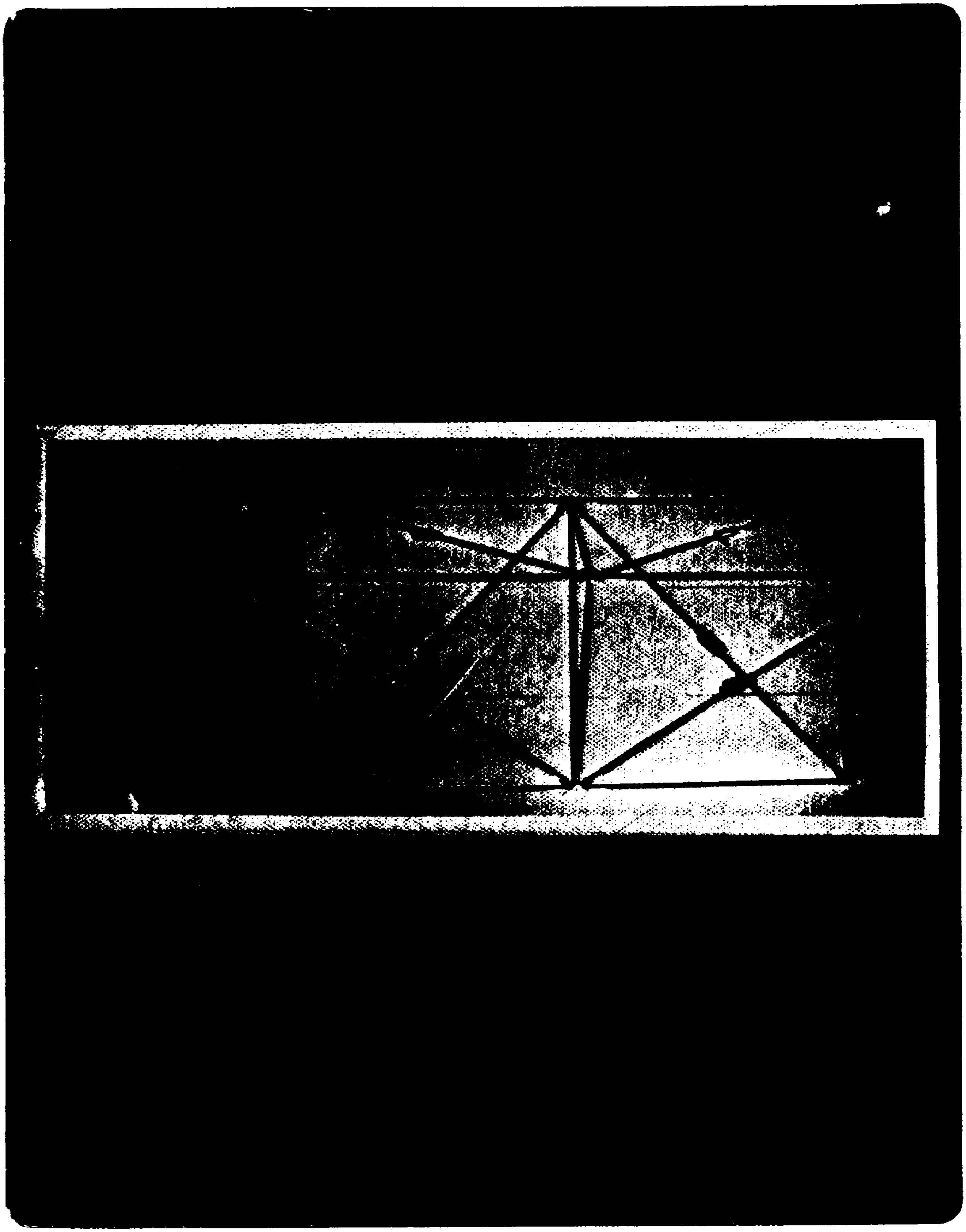
* How does user work with LATDYN ?

* How does program model a system ?

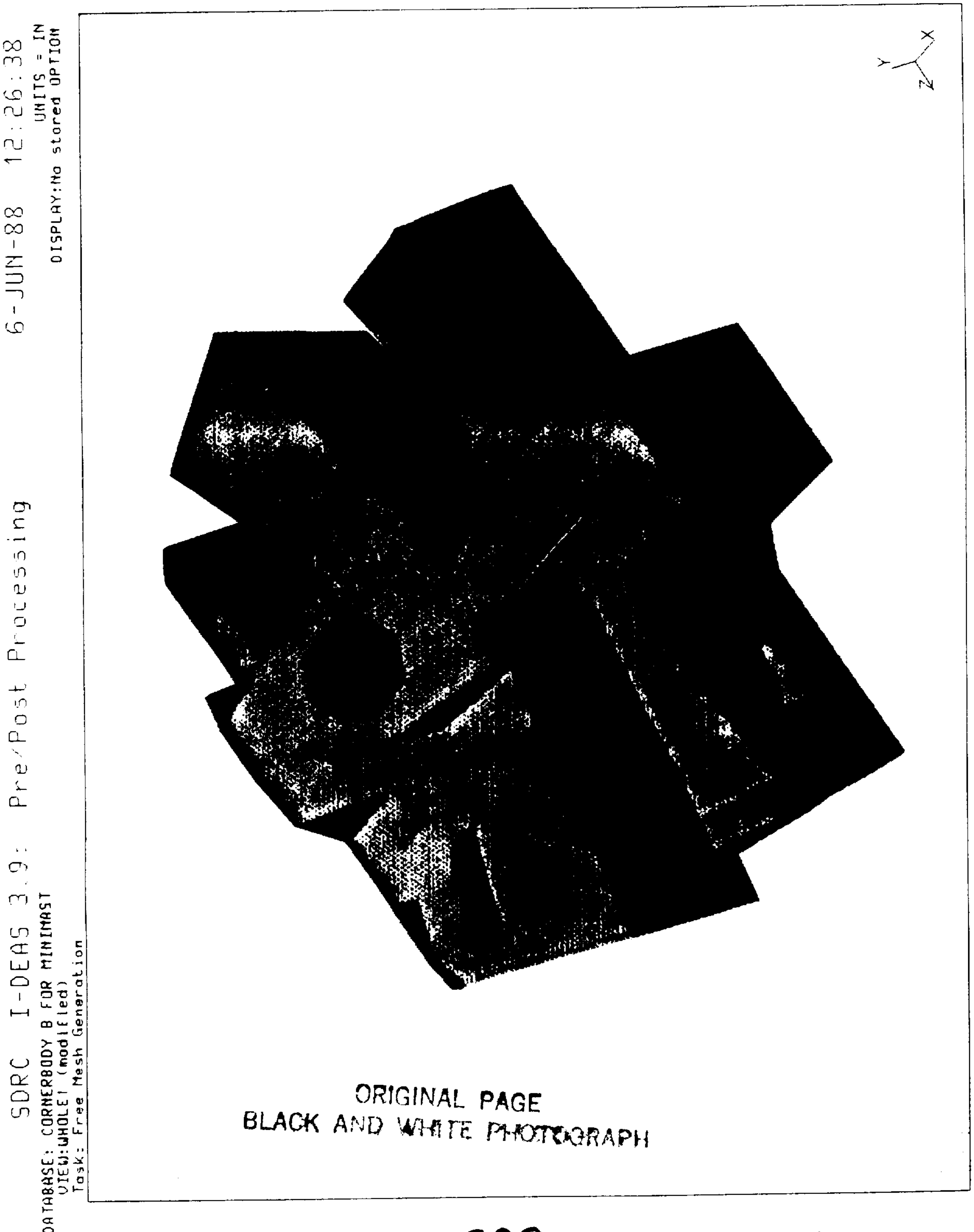

user
modelling commands
programmable language
preprocessor
model data
user's subroutines
LATDYN
dynamic results
postprocessor
output
graphics
user

Defining the Model

1. Numerical Control
2. Flexible Bodies
    * material properties
    * element properties
    * grid points
3. Rigid Connections
    * body geometry & mass
    * joint connections
4. Forcing Elements
    * Forcing functions
    * spring-damper-actuators
5. Initial Conditions
6. programmable language



ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



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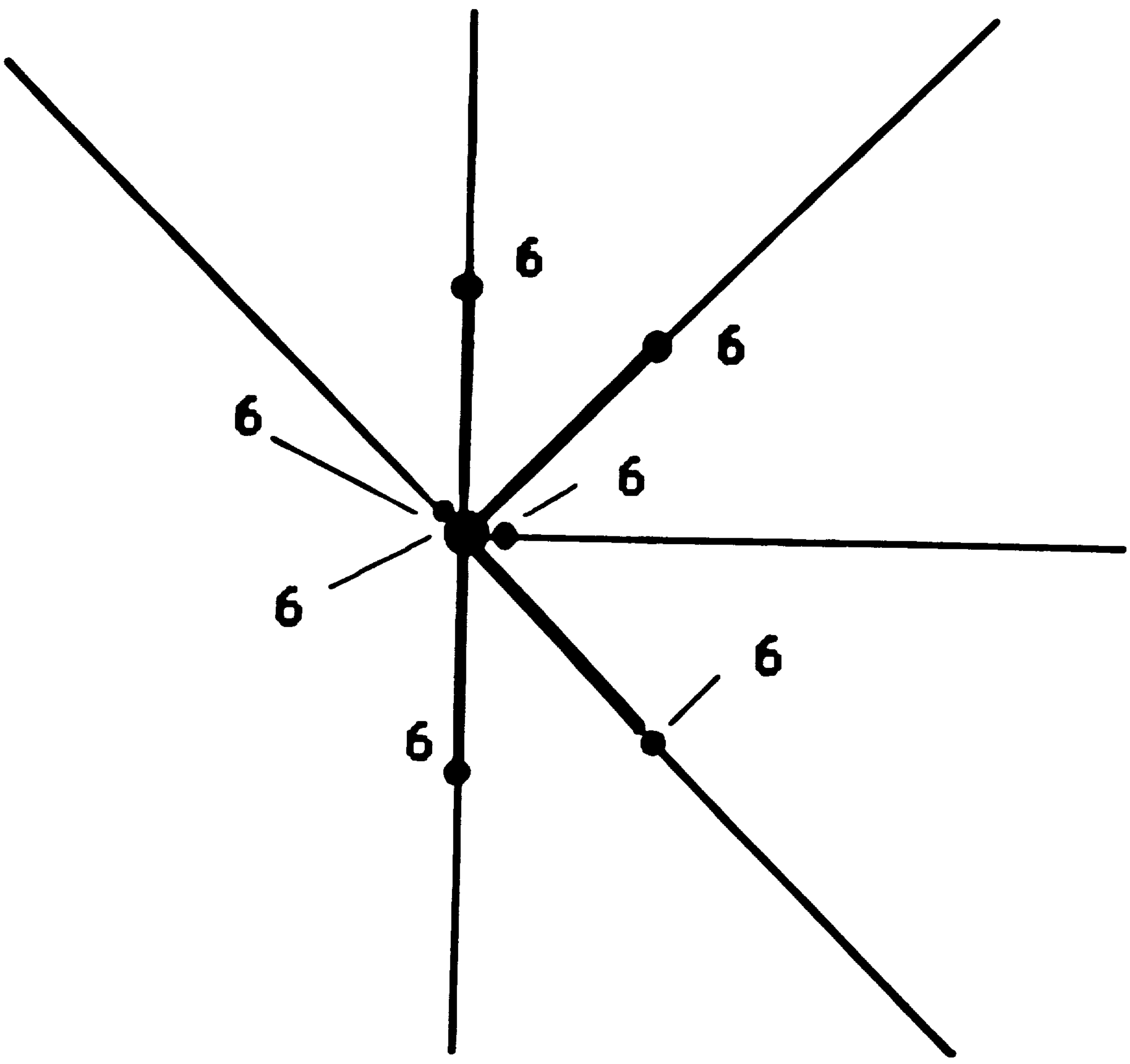
Conventional

F-E Model of corner body

● grid (6-dof's)



42-dof's

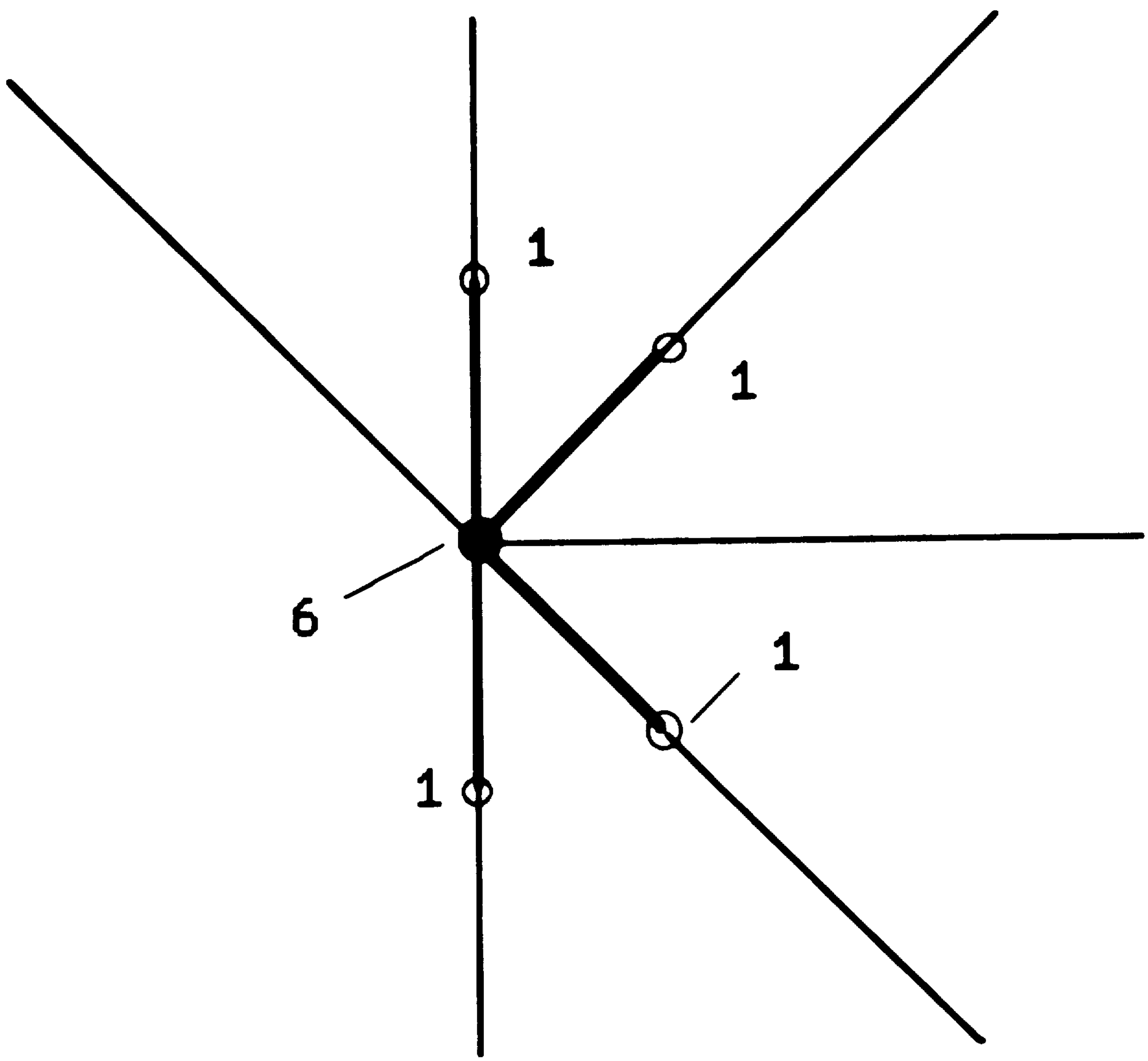
32-constraints

LATDYN

F-E Model of corner body

● **grid (6-dof's)**

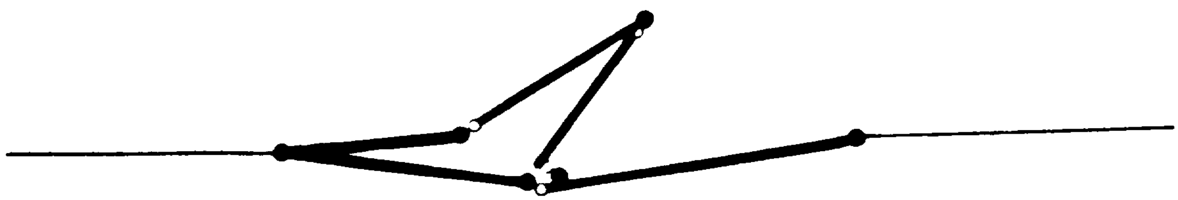
○ **hinge (1-dof)**



10-dof's

0-constraint

3–D LATDYN Model of Mini–Mast Locking Joint



Note: closed loop

Target is that user will not have to specify how rigid members are formulated.

Program will determine most efficient arrangement, and will cut closed loops and implement constraints automatically.

Present LATDYN

* three-dimensional
* Euler-Bernoulli beam elements
* hinge connections
* Newmark-β explicit & implicit methods
* constraints & joints
* external forcing function & spring-damper-actuator

COMPARISON OF RESULTS FOR FLEXIBLE BEAM SPIN-UP ON A PLANE

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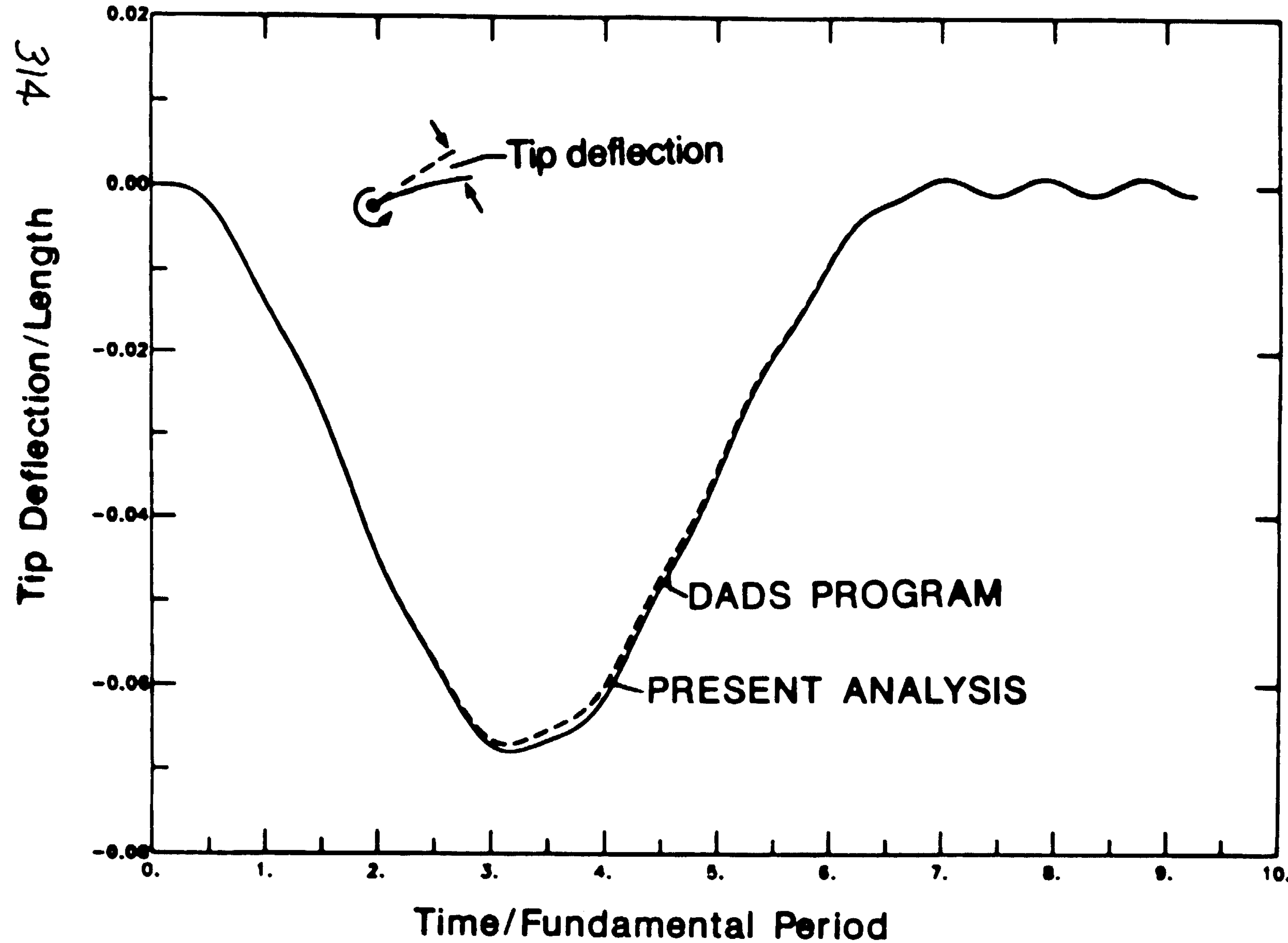
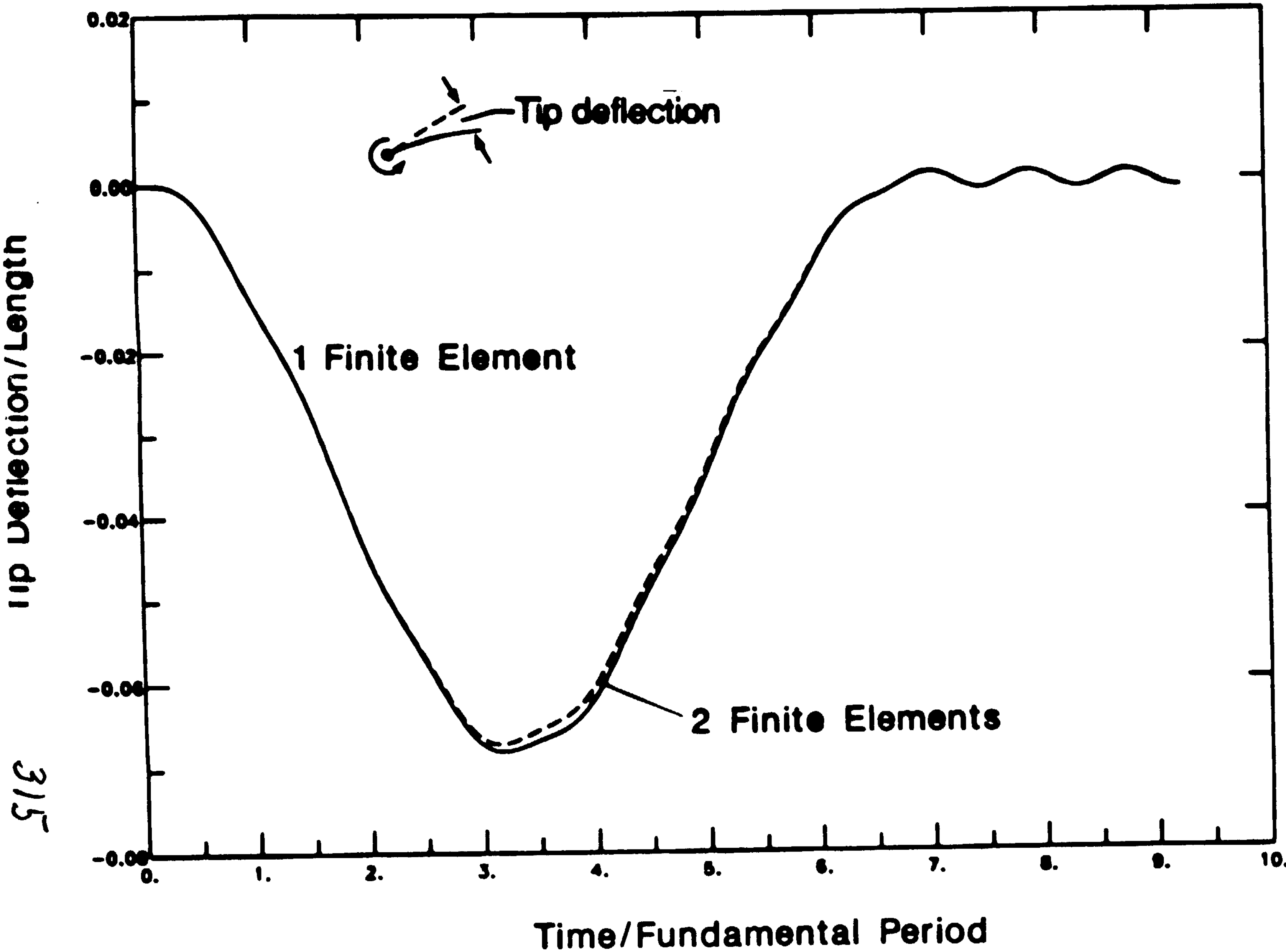
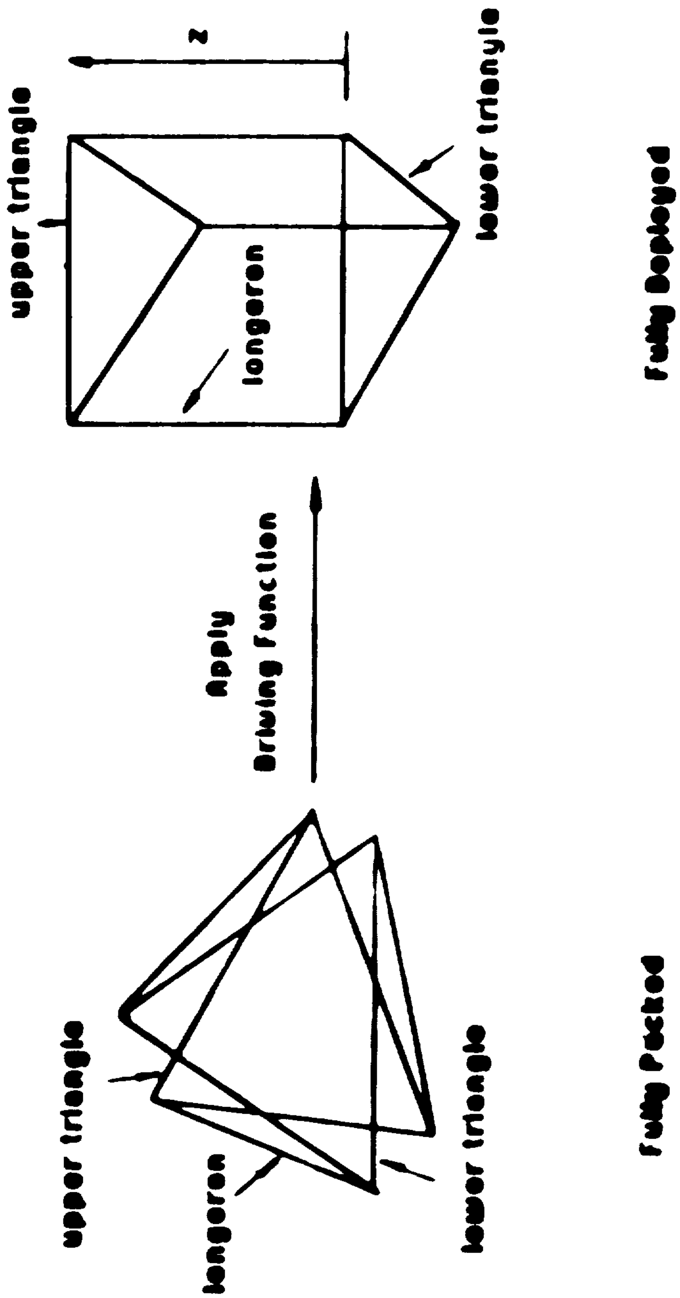


CONVERGENCE OF SOLUTION FOR FLEXIBLE BEAM SPIN-UP ON A PLA





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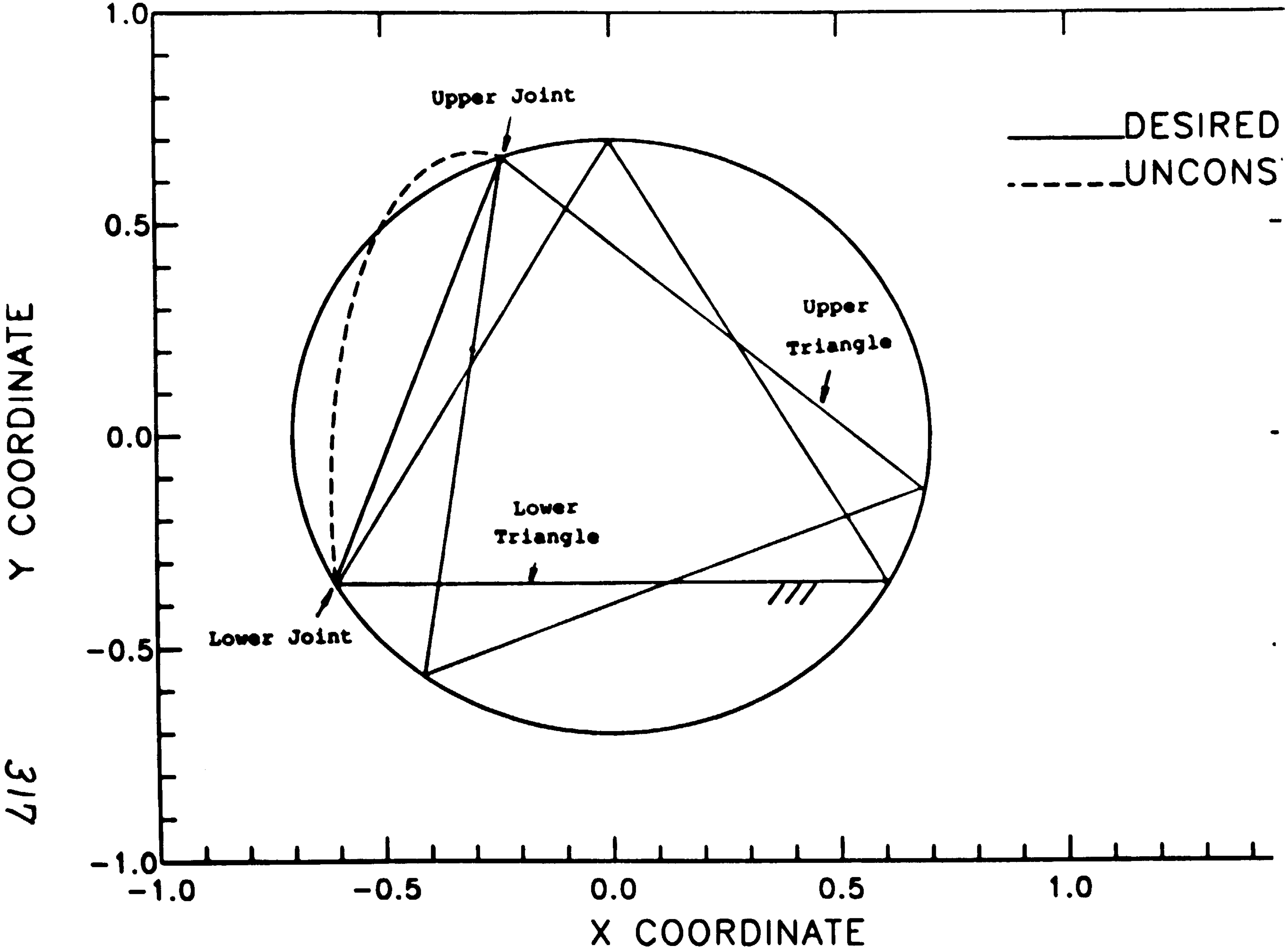
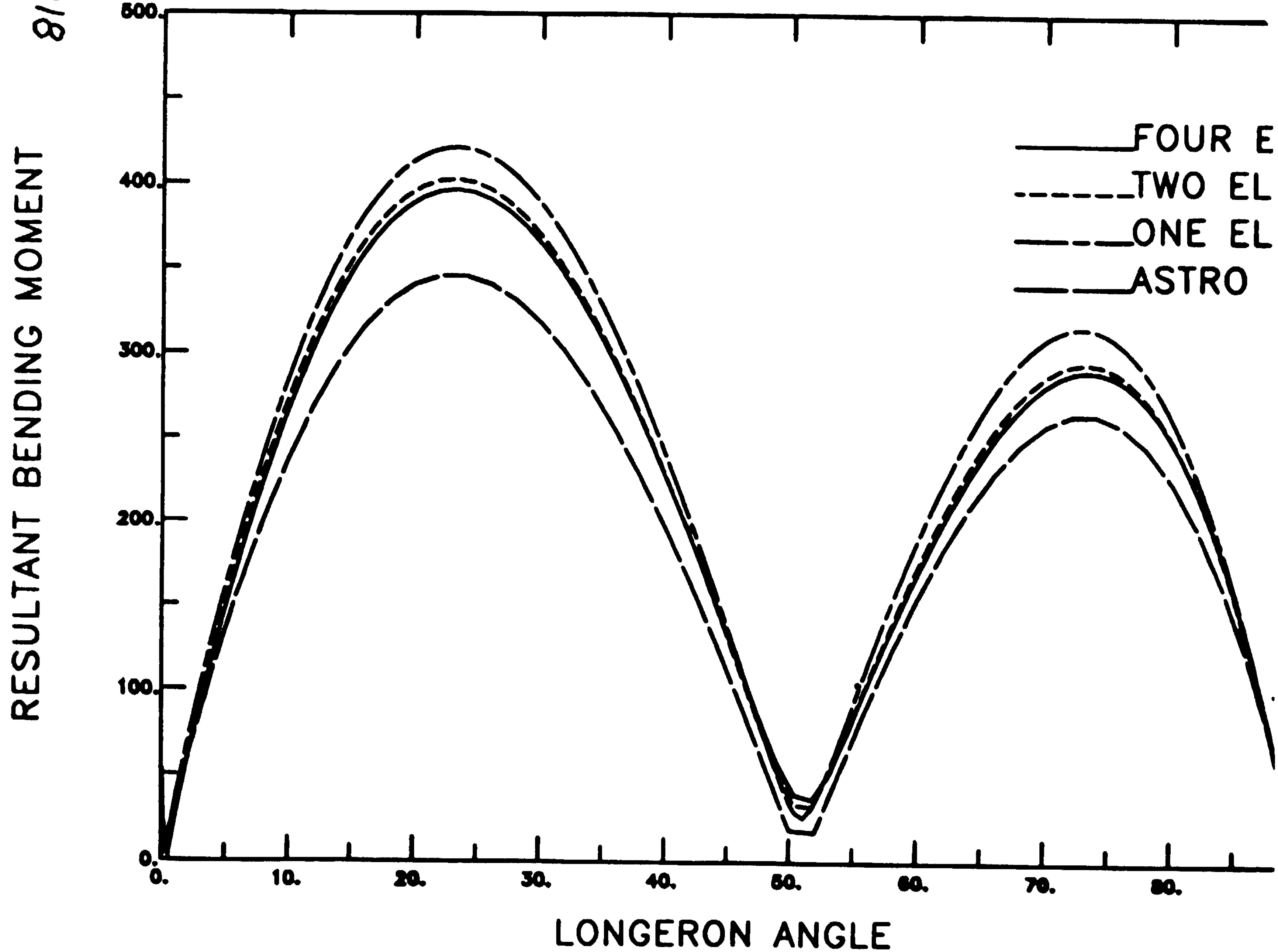

Y COORDINATE
X COORDINATE
DESIRED
UNCONS
Upper Joint
Lower Joint
Upper Triangle
Lower Triangle
1.0
0.5
0.0
-0.5
-1.0


RESULTANT BENDING MOMENT
500.
400.
300.
200.
100.
0.
0.
10.
20.
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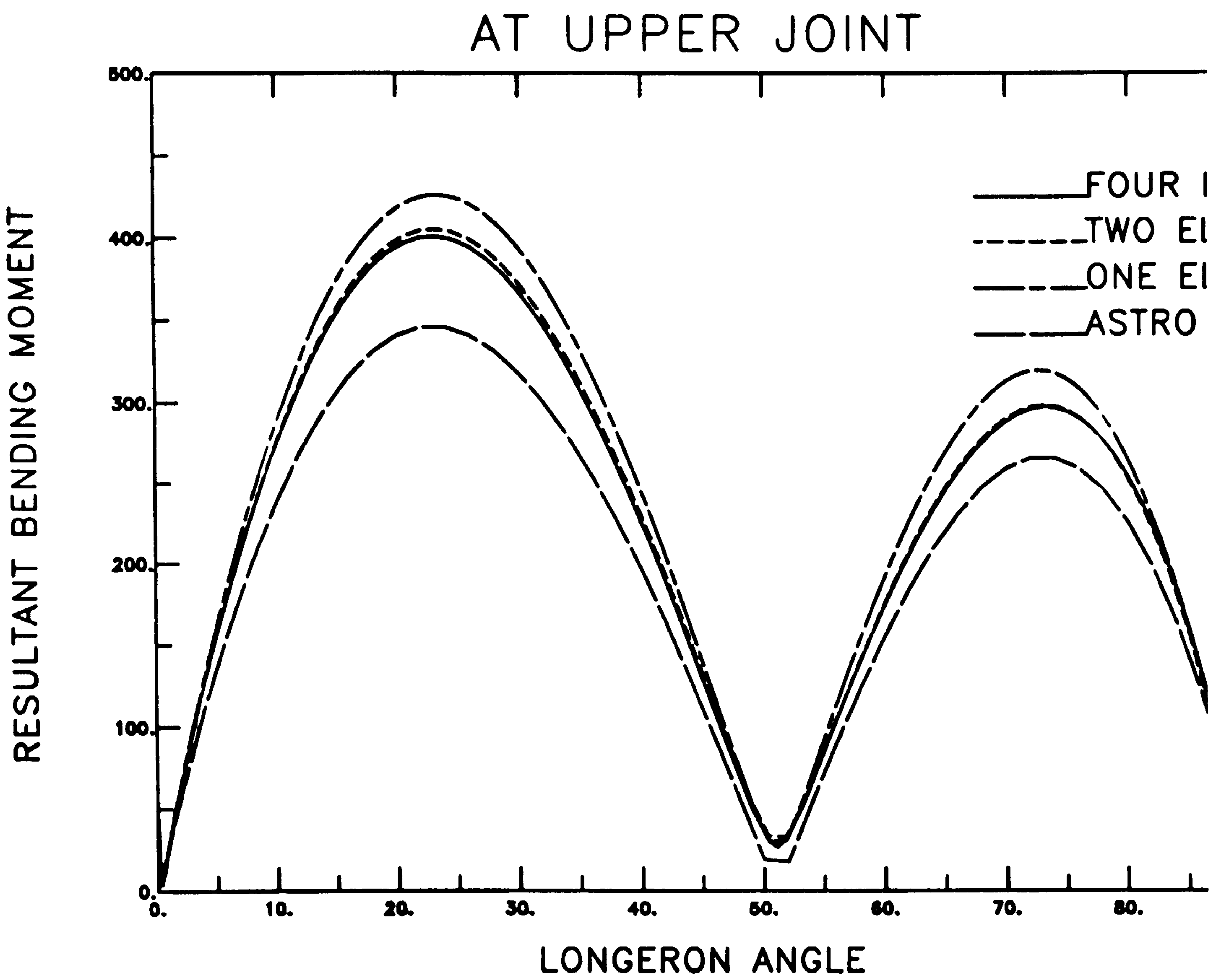
LONGERON ANGLE
FOUR E
TWO EL
ONE EL
ASTRO


AT UPPER JOINT
RESULTANT BENDING MOMENT
LONGERON ANGLE
FOUR I
TWO EI
ONE EI
ASTRO
0.
100.
200.
300.
400.
500.
0.
10.
20.
30.
40.
50.
60.
70.
80.

Future LATDYN

* various elements
* various joint connections
* various integrations
  (parallel version)
* control and structure
  interactions

Conclusions

* A finite-element-based research code is developed.
* It provides a modelling, calculation, and analysis tool for researcher & Engr.
* To analyze complex space structures and/or mechanisms.
* In the simulation of Control design as well as structural dynamics.