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A COMPUTER ORIENTED FORMULATION FOR GEOMETRICALLY NONLINEAR PROBLEMS EINE COMPUTER-ORIENTIERLE FORMULIERUNG FÜR GEOMETRISCHE NICHTLINEARE PROBLEME UNE FORMATION POUR DES PROBLÈMES NONLINÉAIRE GÉOMÉTRIQUE Yutaka YOSHIDA TOKYO INST. TECH. NISHIWAKI MUSASHI INST. TECH. Takeo Nobutoshi MASUDA DERIVATION OF ELEMENT EQUATION 6. FORCE-DISPLACEMENT RELATION IN GLOBAL SYSTEM [EQ. A] 1. COORDINATES x AND DISPLACEMENTS $\mathbf{u}^{\mathsf{T}} = (\mathbf{d}^{\mathsf{T}} \mathbf{\theta}^{\mathsf{T}})$ IN GLOBAL COORDINATE SYSTEM (x y z) $\Delta I = \Delta T^{T}(I_{(n)}^{H} + T_{(n+1)}^{T}K^{H}[\Delta T(I_{(n-1)}^{X})] + T_{(n+1)}^{T}(I_{(n+1)}^{A}K^{H}T_{(n+1)}^{A}\Delta U$ [4d*]/xm (n+1) FUNCTIONS OF UNKNOWN INCREMENTAL DISPLACEMENTS AU n+1-TH EQ STATE (B*) DEVELOP. OF A TWO STEP APPROX. & CORRECT, ITERATION SOL. PROC. In the first two steps, EQ.A is linearized with respect to Δu , before the g^(L) assemblage of element equations. Then in iterations, only Δu_{k+1} are treated as unknowns, others are estimated by using k-th approximation of Δu . וחו [d*,] NUMERICAL EXAMPLES n-TH EQ. STATE 1. CONVERGING PROCESS ILLUSTRATED BY X_H IJFIRST,TWO STEF DEFORMED CONFIGURATIONS STEP APPROXIMATIO ELEMENT INITIAL STATE t =1 $\theta_{(D)} = \theta_{(D)} - r_{(D)}$ φ=215 x₍₁₎=x₍₀₎+d₍₁₎ SCALE) DIMENSIONS EI=106 CONFIG. 12 CORRECTIVE TO SIMENSIONS EI=106 CONFIG. 13 CORRECTIVE TO SIMENSIONS EI=106 CONFIG. 15 CONFIG. 15 CONFIG. 16 CONFIG. 16 CONFIG. 17 CONFIG 2. DISPLACEMENTS uNT=(dNT BNT) IN LOCAL SYSTEM (xN yN zN) $\mathbf{d}_{(1)}^{\mathsf{M}} = \mathbf{\Lambda}_{(1)} \mathbf{d}_{(1)} = \mathbf{\Lambda}_{(1)} \mathbf{x}_{(1)} - \mathbf{\Lambda}_{(0)} \mathbf{x}_{(0)}$ θ<mark>κ</mark>υ=Λ^(U)Θ̄^(U) $\Lambda_{(n)}$: COORDINATE TRANSFORMATION MATRIX 2. SNAP-THROUGH AND BIFURCATION ANALYSIS OF A FLAT ARCH (RISE/SPAN RATIO: 1/100) ONLY BY INCREMENTAL CALCULATION 3. INCREMENTAL NODAL DISPLACEMENTS IN LOCAL COORDINATE SYST. (FROM N-TH TO N-1-TH EQUILIBRIUM STATE) 126/b OIL CLASICAL SNAP-THROUGH $\Delta u^{M} = u^{M}_{(n+1)} - u^{M}_{(n)} = \Delta T \begin{pmatrix} X \\ \hat{\theta} \end{pmatrix}_{(n)} + T_{(n+1)} \begin{pmatrix} Ad \\ \Delta \hat{\theta} \end{pmatrix}$ $T_{(n)} = [^{\Lambda}_{N}]_{(n)}$ $= \Delta T (\frac{x}{\theta - r})_{(n)} + T_{(n+1)} (-\Delta r) + T_{(n+1)} \Delta u$ LOAD S4 SNAP-THROUGH MODE CLASICAL SOL q+q/100 q 4. FORCE-DISPLACEMENT RELATION IN LOCAL COORDINATE SYSTEM BIFURCATION MODE ASSUMPTION OF SMALL STRAIN K*: CONVENTIONAL LINEAR STIFNESS MATRIX 1110511 RISE RATIO a/a

INITIAL STATE

LOAD-RISE CURVES

SPAN L=200

DEFORMED CONFIGURATIONS

5. RELATION BETWEEN LOCAL AND GLOBAL NODAL FORCES

 $T_{(D)} = T_{(D)}^{T} f_{(D)}^{*}$

 $\Delta f = f_{(n+1)} - f_{(n)} = \Delta T^T f_{(n)}^M + T_{(n+1)}^T \Delta f_{(n)}^M$

A COMPUTER ORIENTED FORMULATION FOR GEOMETRICALLY NONLINEAR PROBLEMS



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FORMULATION OF THE ELEMENT EQUATION

An incremental formulation is developed here, under the assumption of large displacement but small strain. The key point of the formulation is the description of nodal locations by the coordinates themselves instead of by mere displacements. A local coordinate system $(x^*\ y^*\ z^*)$ is introduced which is at any time on the element itself, and the element force-displacement relation is assumed to be linear in this local system. The geometrical nonlinearity is considered only through the nonlinear transforming relations of displacement components between the space-fixed global coordinate system $(x\ y\ z)$ and the element-fixed local coordinate system. The transformations are evaluated rigorously without neglecting small terms, so that incremental relations satisfy equilibrium conditions after deformation as accurately as poissible.

SOLUTION PROCEDURE

To construct and solve structural equilibrium equations, an effective corrective iteration solution procedure is also originally developed. The process, outlined in the following, makes use of physical properties of each term in the derived element equation. At first, the changes of transformation matrix and rigid body rotation in the element equation, ΔT and Δr respectively, are linearized with respect to incremental displacement ΔU at the n-th equilibrium state A. And the transformation matrix after the increment, T(n+1), is estimated at the same state A. Hence the element incremental equation is written in the following quasitangential form.

$$\Delta f = (K_f + K_u + K)_A \Delta u$$

Then summing up the element incremental equations thus approximated for overall structure and solving them, the first approximation of the n+l-th equilibrium state C is obtained. Secondly, ΔT and Δr are linearized at the midpoint B between A and C, meanwhile T(n+1) is approximated at the above obtained first approximating state C. Thus the element incremental equation is written as

$$\Delta f = (K_f + K_u + K)_{B,C} \Delta u$$

Thus the second approximating solution, denoted by D, can be obtained. Then afterwards in iterations, ΔT and Δr as well as T(n+1) are all evaluated by using the just preceding approximating solution, and only the incremental displacement Δu is treated as unknown variable. Namely, for the k+1-th approximation

$$\Delta f - h_k = K_k \Delta u$$

is used, where

$$K_k = T_k^T K * T_k$$
, $h_k = T_k^T f *_{(n)} + T_k^T K *_{(\Delta T (\theta - r)_{(n)} + T_k (-\Delta r))}$

and

$$\Delta T = T_k - T_{(n)}$$
, $\Delta r = r_k - r_{(n)}$

The iteration is continued until satisfactory convergence is obtained.

FEATURES OF THE PROPOSED METHOD

- With mere incremental calculations and without special techniques such as eigenvalue analysis, not only snap-through and limit point phenomina but also bifurcation can be pursued.
- Even for an extraordinary large increment, numerical stability exists and sufficient accuracy is obtained.
- As the consequence of the above characteristics, calculating time can be reduced considerably.